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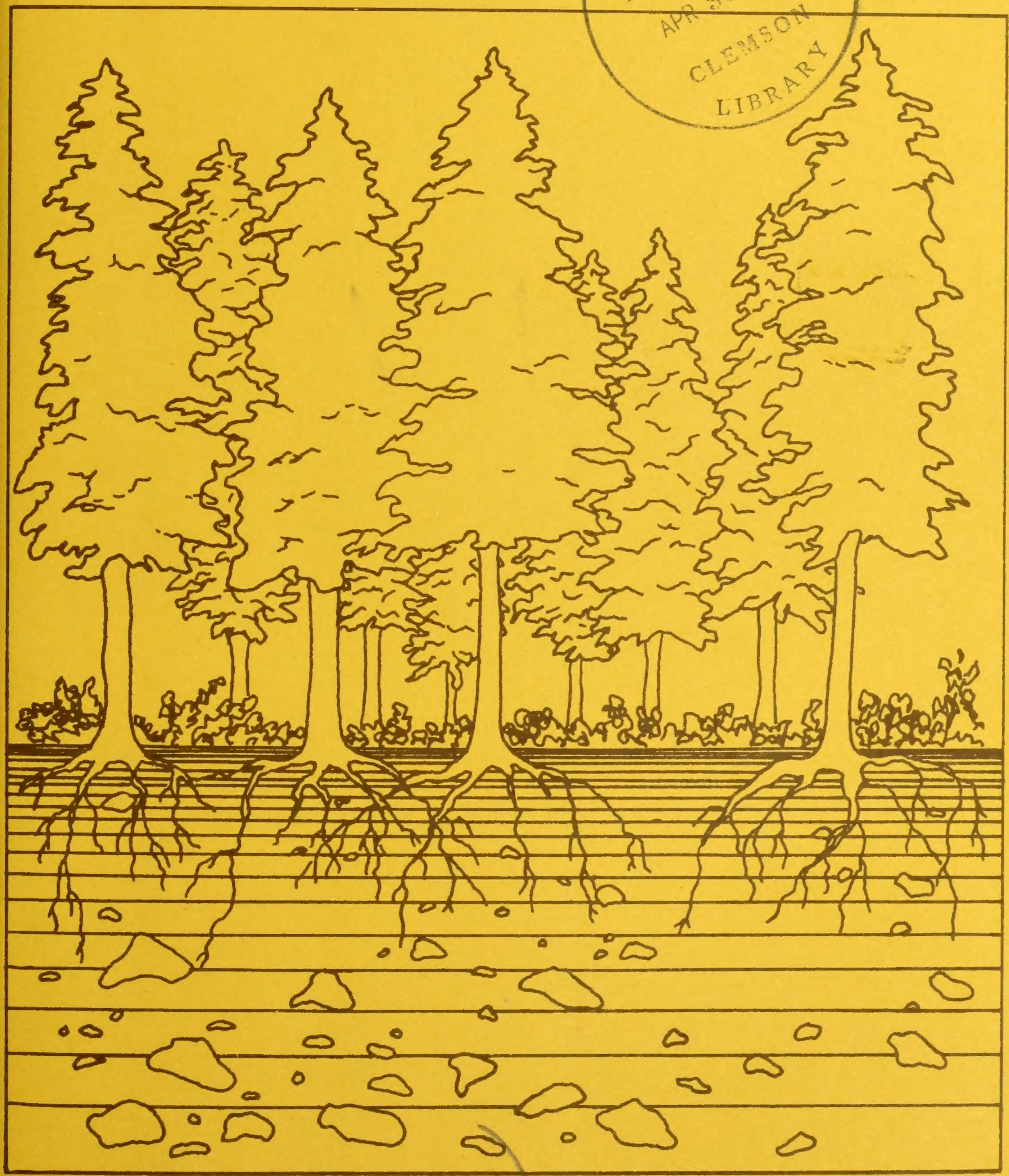

I.U.F.R.O. Symposium on Forest Site and Continuous Productivity

Seattle, Washington
August 22-28, 1982

Russell Ballard and
Stanley P. Gessel
Technical Editors

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PREFACE

This Symposium was planned by members of the IUFRO Site Group (S1.02) as part of their on-going activities to facilitate the worldwide exchange of ideas among individual research workers and to promote the dissemination of research results in the area of forest site productivity. The Symposium consisted of three days of indoor sessions followed by a 2-1/2-day field trip through the forests of western Washington, including the Mt. St. Helens blast zone. The Symposium attracted 130 participants from 15 countries.

Acknowledgments are made to members of the Symposium planning committee: Stan Gessel, University of Washington; Russ Ballard, Weyerhaeuser Company; Chuck Grier, University of Washington; Dale Cole, University of Washington; Dick Miller, U.S. Forest Service; and Bob Powers, U.S. Forest Service. Thanks also go to the session moderators (George Bengtson, Tim Ballard, H. Zottl, Dick Miller, Bob Zasoski, Dick Walker) and Delores Batayola for running the Symposium so smoothly. The fine job done by the field trip hosts, Dick Miller, U.S. Forest Service; Dale Cole, University of Washington; Jack Winjum, Weyerhaeuser Company; and Bill Scott, Weyerhaeuser Company is gratefully acknowledged.

The papers printed in the proceedings all received technical reviews and were edited by both the Symposium editors and the professional editorial staff of the Pacific Northwest Forest and Range Experiment Station, Portland, Oregon. Printing and production were supervised by the Pacific Northwest Forest and Range Experiment Station, Portland, Oregon.

Russell Ballard
Stanley P. Gessel
Editors

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OPENING REMARKS

David B. Thorud, Dean
College of Forest Resources
University of Washington

It is a pleasure to open this conference on forest productivity and to welcome you to the campus of the University of Washington. We are meeting in a general University facility but I will call your attention to the location of the College of Forest Resources on the campus and invite you to spend some time visiting our facilities. I would like to point out that this is a IUFRO meeting representing the Division of Silviculture.

Although the wood commodities from our forests undergo considerable economic fluctuations, and we are currently in a depressed market, the need for forest products by an expanding world population will continue to grow. At the same time, the land base on which we produce forests continues to shrink. In addition, our forest crop production is confined to the poorer soils and those that are more difficult to manage. Productivity of forests on a continuous basis on these soils has probably been developed and sustained over thousands of years under a no-harvest or relatively light harvest regime. Current and expanding forest product needs dictate that accelerated harvests will be made and more complete utilization of the total forest crop will evolve. Harvesting techniques and other forest cultural operations also have an impact on the forest site and on forest productivity.

Concern for this impact and possible change in productivity is evident in much of the environmental literature and even in current forest law in the United States. Despite considerable effort by researchers in the field of forest productivity, it is not clear that we really understand the basis for the widely differing forest productivities that are encountered. We certainly do not have the basis for detecting changes in forest productivity brought on by management and following up with the correct ameliorative measure. Therefore, the discussions in and recommendations from this meeting are extremely important to future forestry.

Your program indicates that you will make a thorough review of forest productivity by first considering what is meant by productivity and the factors that determine the productivity state of any area. From these basic discussions you will move on to the modification of these factors by forest practices and subsequent effects on productivity.

This will be followed by the important subject matter of maintaining and improving forest productivity. The program will culminate with a review of improving the mineral nutrition of forest trees, especially through forest fertilization programs.

A group of experts from throughout the world has been assembled to discuss these subjects. Local participants have a unique opportunity to listen and profit from world experience and research. Although we believe we live in one of the favored forest areas of the world, we have much to learn about managing our forests for continuous productivity. Dr. Earl Stone has a most challenging task to summarize the discussions and enumerate the research challenges of the future.

I regret that I cannot stay with you throughout the conference, but I wish you the best of success in your endeavors and also a pleasant visit to this area.

If there is any way we can make your stay more productive or more pleasant, please let us know.

WHAT DO WE NEED TO KNOW ABOUT FOREST PRODUCTIVITY AND HOW CAN WE MEASURE IT?

E. David Ford

ABSTRACT: National and international surveys highlight the possibility of a dramatic increase in the future demand for forest products and that this may have to be met on a declining land area available to forestry. Under these circumstances four parameters of forest productivity are identified as important but each posed problems in definition and of measurement.
(1) Actual productivity is currently determined and expressed in different ways by economists, silviculturalists, and ecologists. A more united view may develop where attempts are made to increase yield/area.
(2) Potential productivity is difficult to calculate because different factors may control growth as a forest matures. New techniques are required to allow foresters to keep their 'finger on the pulse' of the growth process.
(3) Measurement of the rate at which productivity may be changed is discussed with particular reference to the type of experiments that should be conducted when a dynamic growth process is being accelerated.
(4) Assessing whether or not forest productivity is sustained at a site is a complex task. Long-term changes in weather patterns may influence growth and specific management practices can have dramatic effects during harvest and replanting.

INTRODUCTION

As the first contributor to this symposium on "Forest Site and Continuous Productivity", I feel at liberty to describe some trends in the consumption of wood and wood products, their projection into the future, and particularly to comment on the response of various agencies and people to these projections. This is not a casual task for a forest ecologist, it is an important one in order to define those attributes of forest productivity that are of immediate and developing importance. And these definitions are far from straightforward.

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In the United States the consumption of lumber in 1970 was 33 billion board feet-- 11 percent lower than at the turn of the century. In contrast the consumption of pulp, plywood, and other wood products has risen dramatically during this period; eg., wood pulp from 4,000 tons in 1920 to 43,000 tons in 1970 and softwood plywood from less than 500 million square feet in 1930 to over 13,000 million in 1970 (all figures from Gregory 1972). In a recent study Adams and Haynes (1980) predicted a 53 percent increase in demand in all softwood products between 1976 and 2030. Taken together, these numbers illustrate the important feature of the increase in consumption typical of industrialized nations, that there is an increasing requirement for the processed product. Not surprisingly then, over the last decade, despite the recession in trade, concern has been expressed by international and national agencies that a worldwide shortage of timber may develop during the next 20 to 40 years. This seems particularly likely if the economies of developing countries develop along a similar pattern.

When forming a policy for the European Community, the Commission to the Council of Ministers noted that all member states had a deficit in wood and wood products that was second only in value to oil. They estimated (Commission of the European Communities 1978) that between 1978 and 2000 timber requirements would increase by 2 percent per annum whilst European production covering less than half the requirements in 1978, would increase by only 1 percent per annum if there was no change in forest policy. In the United Kingdom, which in 1976 imported 92 percent of wood and wood products requirement, consumption was then forecast to rise 50 percent by 2000 and 90 percent by 2025 (Centre for Agricultural Strategy 1980). This was considered against the background of a rising world demand estimated as likely to increase by 350 percent for sawn wood and 580 percent for paper products by 2025.

In proposing objectives and principles of forest policy, the European Community Commission concentrated its attention on preserving and protecting existing forests to be managed as renewable resources for timber production, conservation, and improvement of the environment and recreation. Strong weight was given to multipurpose land use and the general role of the forest in the agricultural landscape. Whilst it was suggested that some improvements in silviculture be pursued, no concerted research program has yet emerged specifically designed to increase the productivity of forests for those products most likely to be required in the future. For the United Kingdom, where the potential timber shortage appears at its most dramatic, the Centre for Agricultural Strategy examined a series of options for increasing the area of forest plantation. The maximum possible planting program would double the nation's forest estate and transfer to forestry almost one third of the hills and uplands; and this would result in 26 percent self-sufficiency by 2035. Increased site productivity was not considered as an important component in this balance. Not surprisingly in a country of dense population, this proposed extension has drawn forth protest from nature conservationists and hill farmers and also engineers and hydrologists who are fearful that afforestation of the important upland catchment areas would significantly reduce water yield.

Gessel (1981) recognized the dual problem: that increasing demand for timber products was matched against a declining land base with which to supply them. He stressed the vital importance of increasing productivity per unit area of land and posed the questions:

> Can we prevent losses in current productivity?
> Do our present forest practices improve or degrade future productivity?
> Can we increase productivity and, if so, how?
> And, if we have increased productivity, can we sustain the increase over a long period?

By asking these questions, Gessel is considering no more than the traditional objective of forest management which is to pursue the maximum sustainable yield, save that he considers it essential to reconsider what the maximum really is.

There are, then, four important measurements to make of forest productivity:

(1) Actual productivity. The yield from a forest is not easy to estimate, yet accurate timber inventory and prediction of the yield of standing forest is the essential prerequisite to forest planning both for land managers and those concerned with national or company policies.

(2) Potential productivity. What yield of timber might an area of land produce under improved management and/or higher investment? The limits to forest growth set by species biology, climate, and unchangeable soil factors are only partially understood even for the most studied silvicultures.

(3) How quickly can productivity be increased? This is, perhaps, the least considered of all questions concerning forest productivity, yet it could be the most important. The major limitation to increasing timber supply in the short term, say 5 to 10 years, is likely to be the capacity of the forest industry to harvest an increased output from the growing "capital" of the world's existing forest. This can be viewed simply as an investment decision and one adequately controlled by socio-economic patterns. But a more fundamental question is: Can forest productivity be increased to match widely predicted and large increase in demand?

(4) What yield can be sustained at a site? The basis of high yield agriculture is continuous investment in herbicides, fertilizers, and pesticides as well as continuous improvement of growing stock through breeding for disease and pest resistance and higher harvestable yield. Actual yield may be increased closer to potential, perhaps by the simple technique of fertilizer application, but the experience of agriculturists is that both the ecological and economic conditions of high yield are such that one such improvement requires other actions to maintain it. What we require is an estimate of the management intensity required to sustain a unit increase in productivity.

These problems, the estimation of actual production, the calculation of potential, assessment of the rate at which improvements can be achieved, and the degree of management effort to sustain them - should not be thought of as abstruse and only relevant to theoreticians of large-scale industrial forestry and national agencies. If world demand for timber continues to increase, as many assume it will, then the everyday operations of forest managers will be influenced by these problems.

ACTUAL AND POTENTIAL PRODUCTIVITY

The concept of potential productivity (rate of increase in dry weight per unit area of land per unit time) was developed by crop ecologists.

A theoretical estimate of the optimal conversion of light energy into chemically bound energy can be made using a figure for the quantum efficiency of photosynthesis, ε, and assumptions about respiratory loss. Potential productivity provides a yardstick against which to measure actual productivity. With such a technique Black (1964) attributed the relative losses in production of clover crops in South Australia as between summer drought, an inadequate development rate of leaf in the early spring, and excessive leaf amount in autumn. This technique has proved valuable in analyzing the factors controlling the growth of other agricultural crops; e.g. grasses (Alberda 1971). The underlying philosophy is not, how can we improve yields? but, how can we attain maximum yield?

However, it is important to note that in such analyses agriculturists have generally worked with a clear definition of crop yield and assumed that certain basic aspects of farming practice hold throughout the situations they considered. Undoubtedly the concepts of actual and potential production could be used by foresters to assess the possibility of increasing yields (e.g. Ford and Fraser 1968) but they must be expressed as well-defined and quantifiable parameters. An estimate is required of by how much the actual productivity of a site is below its potential: but for forest crops the problem begins with definitions of productivity.

Forestry is a complex activity involving people with different professional backgrounds and with differences in the definition, measurement, and expression of productivity. There is no single parameter of forest productivity that can be measured with certainty and to universal satisfaction. Economists, forest managers, silviculturists, and forest ecologists each measure productivity (table 1) in a manner suitable to express those aspects of the forest as a working system, with which they are particularly concerned.

Each of these measures poses major problems even within the originating discipline. The forest economist must make assumptions about land value and encounters difficulties in matching the time scales of forest operations and financing. Forest managers and silviculturists measure timber volume which in itself is of restricted value without a description, albeit implicit, of timber quality. The ecologist has the refuge of the definition of dry weight gain that appears theoretically satisfying in its comprehensiveness but is difficult to measure accurately and relate to timber yield, particularly for large stands.

Agriculturists do not face the same problems. First, crops are grown on an annual cycle. Second, the expression of crop quality, while not always simple, rarely presents such a complex set of options such as those found where thinning regime, harvest time, and stand assortment interact. Third, for many agricultural crops, biological productivity and harvestable yield are linked by a single parameter - the harvest index. Direct study of the harvest index has been the foundation of significant improvements in yield (Evans 1976). Agriculture is product oriented and everybody is generally agreed what the basic objectives are.

In forestry, the concepts of actual and potential production will be of most value where a clear definition of production can be made in relation to a specific utilization. Zavitkovski (1976) noted that whole tree utilization and pulping systems require that forest products be measured in weight rather than volume and described the calculations necessary to assess the efficiency of conversion of solar energy by intensively managed forest stands. A more general example of clarity in definition of yield leading to improvements is to be seen in New Zealand forestry. There the production thinning regime, which has the attribute of producing yields of a wide range of types of

Table 1. Measurements of forest productivity made by different professionals in the forest industry and some problems associated with each.

	Measure of productivity Yield/resource/time	Problems
Economist	£/ £/ year	Financial definition of the resource. Considerations of time scales for investment and forest growth.
Forest manager-silviculturist	Timber volume/land area/rotation	Timber quality, relating yield to timber value.
Production ecologist	Dry weight/land area/year	Measurement of dry weight gain.

timber during one rotation, is being replaced in some areas by a silviculture specifically designed to meet an export oriented log market with a clearly defined product (Fenton and Sutton 1968). This has stimulated research to meet a number of specific problems mainly associated with improving timber quality and the formulation of research goals has become a more unified task within the forest industry (Theron 1981). For such silvicultures the profitability of particular forest stands is dependent upon a particular market for timber, and the confidence to allow this to happen depends upon market conditions. If some diversification is required this can be achieved by balancing the use of different silvicultures across the forest estate. Diversification is not essentially dependent upon the maintenance of a single silviculture designed to produce a universal range of products from each piece of land.

I do not argue that a change to single-product silvicultures should take place but rather note that these are being developed, frequently based on short rotations with intensive culture and intimately linked to a particular processing (Kromhout and Bosman 1981, USDA Forest Service 1976). I suggest we may look on this as part of a continuing evolution of forestry from an industry exploiting a resource to one utilizing, and integrated with, specific cultural systems. This process may accelerate if and when demand for timber accelerates, particularly for industrial uses. The increasing use of plantation forestry can be seen as one stage in this evolution, though in many cases plantations have been established to replace over-exploited natural forest, and for various reasons no clear, product-orientated objective has been formulated for these silvicultures.

Site Studies

In early studies of forest productivity the quality of a site was characterized by the actual growth achieved. Crop growth was used as a bioassay of site conditions with tree height as the measured parameter because height was considered the attribute of growth least influenced by factors external to site influences, e.g. differences in stand density. It was assumed that stands on sites of the same quality would follow the same tree height: stand age curves and site index assessed as the height that would be reached at a specified age, usually 50 or 100 years. This generalized approach has been found wanting. Carmean said (1975) "height growth patterns vary greatly (are polymorphic) for many species that grow on contrasting sites or that have wide geographic distribution." That is, stands may have the same height at one particular age (e.g. 50 years) but different heights at other ages, and so their courses of growth cannot be predicted with sufficient accuracy for management purposes by a family of non-intersecting curces.

A distinction must be made in the more recent developments that have taken place in site studies attempting to relate growth and site conditions, even if this distinction is not always clearly made by the investigators themselves. On the one hand, a primary objective has been to predict site index from physiographic and other site variables. A survey is made of established stands and equations sought that relate site index to site factors. When prediction as a management requirement is the prime objective any factor may be included in the measurements whether or not they have any bearing on the tree growth process. On the other hand, studies are conducted where the variables used are intuitively thought related to the growth process. I do not decry the first approach, it is concerned to develop an important predictive tool for current management but it is the second approach which at first sight may seem likely to offer a quantification of the factors controlling actual production and in terms that may give some indication of potential.

A recent study illustrates these two approaches: the investigation of site influence on growth (Blyth and MacLeod 1981a) and the development of predictive equations for actual yield (Blyth and MacLeod 1981b). The local yield class of Sitka spruce, climate, physiographic and soil variables were measured in 73 0.01 ha plots within 12 forest blocks distributed throughout northeast Scotland. The investigation was similar to many conducted with different crops and in different environments (e.g., Carmean 1975) save that two climatic variables, rainfall and temperature, were estimated by repeated measurements at the sites over a year rather than by the more usual method of interpolation from climatic maps. A number of interesting, statistically significant correlations were found between yield and environmental variables that can be anticipated as directly influencing growth (see below). However, these variables were not the most useful as predictor variables for yield. As found with other similar studies the best predictor variables were found to be the more indirect assessments of environment, e.g., depth of the soil at which mottling occurred, depth of the soil organic layer, and position on the slope.

The difficulties encountered in attempting to analyze the factors that control growth from site surveys are many. I suggest that the most important are:

1. The selection of variables for inclusion in the analysis. This is usually made as a compromise between intuition, the desire to be comprehensive, and the ease with which measurements can be made. Blyth and MacLeod (1981a) found that, for all plots taken together, local yield class was most significantly correlated, with winter rainfall (positive), a relationship the authors were at a loss to interpret, particularly since conventional wisdom has it that excess soil moisture and winter waterlogging are the bane of upland forestry in the United Kingdom. The second highest correlation was with soil temperature which they had measured using a sugar tube technique.

In a previous survey of Sitka spruce-site relationships, which encompassed part of the same surveyed area, Malcolm (1970) did not detect these relationships as he had not been able to include direct estimates of the variables.

2. Environmental variables are correlated. For example, Blyth and MacLeod (1981a) commented that the influence of rainfall amount on yield was obscured by the relationship between rainfall amount and elevation which, in turn, was negatively correlated with both air and soil temperature.

3. The assessment of soil conditions. One of the perennial problems in site survey is obtaining a suitable description of soil nutrient status. Blyth and MacLeod (1981a) found positive correlations between local yield class and both total N and total P in the soil organic horizons. Other researchers have only found correlations after making various forms of extraction from the soil designed to simulate the availability of nutrient to the tree.

4. The restriction of sites surveyed to within a narrow age band. Blyth and MacLeod (1981a) limited the age range of surveyed sites to between 20 and 42 years, i.e., covering only 44 percent of the crop rotation. They justified this on the grounds that the effect of site factors on growth may change with the growth of the crop. This is certainly so as forest growth is a dynamic process (e.g., Ford in press), and critical changes take place in the carbohydrate, water, and nutrient balances of stands as they age.

5. Different relationships may be obtained in different sub-regions of an investigated area. Thus, while Blyth and MacLeod (1981a) found a positive correlation between rainfall during the growing season and local yield class in two strata of an elevation classification, they found negative correlations over two separate forest blocks. Interpreting such phenomena can depend upon assessing variation in the absolute quantity of the variable or variables responsible. Straightforward correlations between environment and growth are most often found towards environmental extremes (Ford and Milne 1981) and this may account for some of the apparent differences found between different sites.

These problems, taken together, make site survey a blunt intrument for detecting how environmental factors control growth and for quantifying relationships. But should we scrap the technique entirely or can we work to improve it? The greatest single improvement that could be made is for the selection of variables to be more closely related to the growth process. If fewer, more pertinent variables could be selected then surveys could be more comprehensive in both their geographic and stand age ranges. Ideally, measurements are required that are based on physiological knowledge and provide a 'finger on the pulse' of the growth process.

Forest Eco-Physiological Studies

It is unlikely that the potential production of any forest crop can be specified in terms of a single environmental factor as Black (1964) was able to do for subterranean clover in terms of the solar radiation climate. The exception to this may be where trees are grown at the extremes of their range, but attempts to achieve high production are likely to be made in regions of better growth, and it is in such conditions that the almost unique property of forests comes into play. That is that the growth and development of the forest itself comes to have a significant influence upon the conditions under which future growth is made. For example, as far as the control of nutrients on growth is concerned, rapid early growth depends upon the nutrient capital of the site, but later growth may depend upon conditions that influence the rate of nutrient turnover (Millar 1981). Similarly, considering the utilization of solar radiation, rapid early growth may depend upon the rate at which a foliage canopy is established (Cannell 1979), but subsequently, more subtle aspects of crown architecture may influence growth rate (Jarvis 1981). Forest stands, particularly coniferous forest stands, achieve remarkably high productivities but only for short periods which come comparatively early in their development; i.e., just after canopy closure (Ford 1982) when a maximum exploitation of site resources is achieved. Thereafter there are at least three negative feedback mechanisms that may check growth: (1) the accumulation and slow release of nutrient usually from the litter layers, (2) the increasing biomass of trees to which may divert an increasing proportion of photosynthate to respiration so leaving less for growth, and (3) once a canopy is formed and trees gain in height then a smaller proportion of rainfall may reach the forest floor as a result of increased interception loss. Declining growth rates are an integral part of the development of natural forests and often lead to an increasing susceptibility to disease and render the forest prone to catastrophic destruction. However the precise eco-physiological causes of such decline are rarely easy to define.

These eco-physiological processes and their interactions are discussed in more detail elsewhere (Ford in press). There are two important implications for more intensive culture. First, it may not be easy to identify which mechanism is limiting growth as stands age. For example, fertilization does not invariably produce increased growth when applied to pole stage stands, and for fertilizers to be effective may require that a thinning be carried out at the same time which suggests possible limitations in soil temperature or moisture or perhaps even insufficient surplus photosynthate in unthinned trees. It is in such stands that we need to be able to put our 'finger on the pulse' of growth. Second, an important trend in modern silviculture is towards shorter rotations. This may be for financial reasons, short rotations do pose silvicultural problems, particularly of wood quality, but they may avoid an extended period

during the crop cycle when negative feedback systems come into operation to check growth and which may be difficult to break by cultural techniques.

Of the three major functional cycles carbon, water, and nutrients improved measurement techniques for water and nutrient are most likely to be developed in the near future. The carbon balance of a forest is the result of photosynthetic and respiratory activity; and while there may be good theoretical grounds for considering both as indicators of productive activity, both are distributed diffusely through the forest which makes them difficult to sample. Whole-forest estimates of CO_2 flux, even, if they were technically possible over a sustained period of forest growth would be of limited value since they would not distinquish between respiration and photosynthesis.

Water as a Factor in Forest Productivity

Over the past decade there has been increasing awareness of the importance of water relations to tree growth and productivity. Much of this work has been physiological, but recently Waring et al (1978) related an estimated foliage amount of forest stands along ecological gradients in Oregon to a calculation of the relative potential transpiration of the site.

Penman (1971) documented the relationship between the efficiency with which an agricultural crop utilized the solar radiation it received in the growth process and crop water use. The equation for efficiency is:

$$QY = \varepsilon R_I$$

where Q is the heat of formation of plant material (4 000 cal g^{-1}),

Y is the yield (g. cm^{-2}),
R_I is the radiation income (cal cm^{-2}), and
ε is the efficiency of conversion.

For agricultural crops in southeast England when water supply was not limiting plant growth, the measurements showed:

$$QY = \alpha E_T \lambda$$

where E_T is the accumulated potential transpiration for the period (cm)

λ is the latent heat of vaporization of water (590 cal g^{-1}), and
α is a constant, dependent on management variables other than water supply.

Penman suggested that for southeast England when water supply is not limiting about one quarter of the radiation received is reflected from a green crop and one half of the remainder is used in evaporating water. From measurements he gave:

$$\alpha = \varepsilon/0.38$$

so $Y/E_T = 39\varepsilon$ tonnes, ha^{-1}. cm^{-1}.

This gives a measure of the rate of loss of yield incurred by lack of water or, for a given summer total of E, it gives a maximum yield to be expected for any ε.

For forests, where accurate determination of dry weight gain is so difficult, it may not be possible to solve these equations completely by direct methods. But a significant insight into how water supply controls growth may come from actual measurement of transpiration and a study of how this actually relates to potential transpiration. In practice this resolves to be a study of the two biological parameters specified in the Penman-Monteith equation (Monteith 1965) that predict the rate of transpiration under given meteorological conditions. These parameters are, g_s the stomatal conductance represents the rate at which water vapor passes from the tree into the air immediately surrounding the leaf or needle and g_a, the boundary layer conductance represents the rate at which water vapor is conducted from air around the needles to the atmosphere above the crop.

The parameter g_s can be measured directly with a porometer (Jarvis 1981); it is generally much lower for trees, particularly conifers, than for agricultural crops; that is, there is a greater resistance to the passage of water. g_a is generally very high for forests because their canopies are well ventilated by the wind. Under most circumstances g_s would be expected to be the controlling influence on transpiration from a forest canopy. While it is a parameter that we can measure directly at the leaf or needle making it extremely useful as an eco-physiologically based indication of water relations two important considerations must be born in mind. First, g_s may be influenced by a range of factors from the soil upward which can control the rate of water supply to the leaf as well as atmospheric conditions which can control the rate of loss from it. Second, measurements of g_s may not be easily translated into estimates of total transpiration from a canopy. To do this g_s must be multiplied by the total area of foliage in the canopy and considerable variation in g_s can exist between foliage of different ages and at different positions (Leverenz et al. 1983). Furthermore, the estimation of foliage area when divided between different categories of foliage is not simple, particularly in dense conifer stands.

A most important development is currently underway, that is the application in forest eco-physiological studies of an instrument which will measure transpiration directly as it takes places from the canopy (Hyson and Hicks 1975). The technique is based on the eddy-correlation method already used to measure the rate of heat transfer from canopies (e.g., Milne 1979) and used in conjunction with the basic heat balance equation to estimate transpiration indirectly. Such intruments must be used carefully; they do not distinquish between transpiration and evaporation from the wet canopy, and the horizontal variation of transpiration across a

forest may require considerable investigation. Nevertheless, when operated in conjunction with porometry and other measurements that aid interpretation of the water status of trees, the measurement offers considerable potential for characterizing the site water balance.

A Biossay for Tree Phosphorous Status

Phosphorous is widely known to be one of the most important elements controlling tree growth, but the direct assessment of phosphorous availability by routine analysis of forest soils has proved difficult. Particular problems are the role of organic phosphorous (Dalal 1977), the complex nature of soil phosphorous chemistry, spatial and seasonal variation in the phosphorous cycle, and the dynamic nature of the phosphorous cycle in the forest. Needle analysis of phosphorous has proved a reliable indication of the growth of trees up to 6 m where soil phosphorous levels have been varied experimentally but is much less reliable for larger trees.

Dighton and Harrison (1983) have recently developed a bioassay for determining phosphorous status. This bioassay is based upon the rate of uptake by detached tree roots, of ^{32}P-labelled phosphorous from a standard solution. Trials of the method to assess experiments covering a range of fertilizer applications with Picea sitchensis and Pinus contorta have established that rates of ^{32}P uptake are negatively correlated with rates of fertilizer given with tree heights. Phosporous content of 1-year-old needles were not significantly different between treatments.

Bioassays of this type have great potential for forest site studies. It is important, however, that the range of factors that may influence the numerical values obtained be well understood. Among these might be included short-term variations in the root or plant environment as related to the annual cycles of growth. However, such measurements have advantage that they can be used in conjunction with experimental variation over a wide range of growing conditions.

HOW QUICKLY CAN PRODUCTIVITY BE INCREASED?

A repeated concern about the increasing wide demand for wood is that it may accelerate much more rapidly than the growth rate of forests can be made to increase. If this proves to be the case, then the relationship between demand and supply as dictated by growth rate, price, and investment will have turned out to be very different from that for agriculture. At various times in the past, worldwide food shortages have been predicted, but while serious famines do occur in specific areas the increase in agricultural productivity has been staggering, particularly, but not exclusively, in industrialized countries. Jones (1971) in reviewing post-war British agriculture noted a doubling of wheat production, a trebling of barley and meat production, and an overall increase in agricultural production by one third in the 17 years from 1950. The main contribution to this and similar increases in other countries has been advances in the application of science and technology. Bawden (1969) noted, in comments on the long-term Broadbalk winter wheat experiment which has been running at Rothampsted since 1852, that the fundamental ingredient in the receipe for high yields, the application of mixed ammonium salts, was known 100 years before it became usual practice in England. Its implementation had awaited advances in education and industrial chemistry and, most important of all, changed economic circumstances.

Is the production of wood substantially different from that of agricultural products so that productivity may lag behind demand and shortages develop to damage world living standards? I suggest we need to investigate this from two aspects: (1) the likely response of established forests to techniques designed to raise their growth substantially and (2) factors that may limit establishment of new high-yielding silvicultural systems designed to feed specific industrial processes.

The application of fertilizers, particularly nitrogen, can increase growth of established forests on a large scale. This was practiced in Sweden 15 years ago with the specific objective of leveling out a temporary national timber deficit that threatened the continuous production of the forest industry. But this application, although extensive in area, was limited to a single application of urea. There was no attempt to achieve a permanent increase in productivity.

Generally experiments with forest fertilizers are of the impulse type (fig. 1), that is they involve only a single application of nutrient. Such experiments provide information on the possibility of effecting, what in terms of the total yield from a stand over its lifetime, is a small increase. Like other biological systems, forests are dynamic in their response to change and the typical response of a dynamic system to an impulse is to return to the previous level of performance following the perturbation although sometimes they overshoot into decline. Of course forest growth rate is not constant over time as is the basline output of the system represented in figure 1 and any applied impulse must be assessed against a trend in growth. Millar (1981) concluded, on reviewing results from impulse type experiments that yield from the crop was brought forward in time but not increased in total over the rotation. However, there are two main difficulties in considering the impulse type nutrient experiments with forests. First, the essential aspect of response to an applied nutrient impulse is a "carry-over" or lag effect. The effect which addition of a quantity of nutrient has depends upon the size of the pools of nutrient already

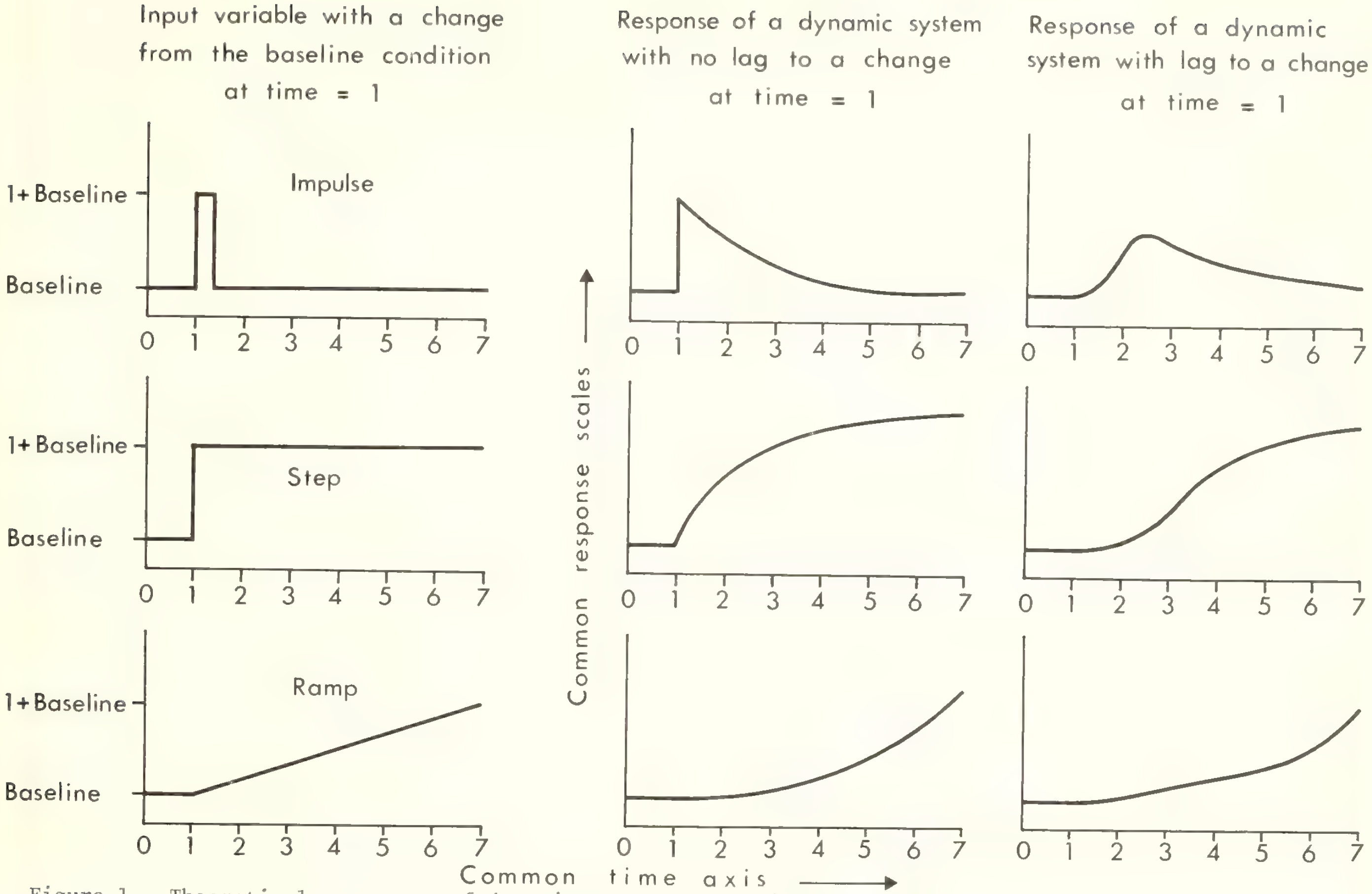

Figure 1.--Theoretical responses of dynamic systems to variation in inputs. Quantities of the dependent variable of the dynamic system are not strictly comparable between the graphs and are controlled by properties of the dynamic system unspecified in this example. (see Milsum 1966).

existing in the forest and the rates of exchange between them (Millar 1979). Although the response of a system with lag is shown, the patterns in Figure 1 are more related to the effects of changes in conditions rather than quantities. Second is the consideration of just how the nutrient conditions of a tree should be assessed in relation to the amount of nutrient it should receive. On the basis of seedling experiments, Ingestad (1982) has suggested that fertilizer should be applied on the basis of a nutrient flux density corresponding to the consumption potential of the trees. He suggested that under such circumstances nitrogen consumption is high and there would be a positive feedback on the soil organic matter mineralization rate and a long-term increase in fertility.

At first sight, it may seem that experiments more pertinent to determining limits to production set by nutrients are ramp or step changes (fig. 1) in nutrition. However, these experiments would have complications over the usual ramp and step experiments made with dynamic systems (Milsum 1966) because quantities rather than conditions are being manipulated, and the formulae used for application rates would have to be carefully considered. Consider a step change in nutrition as an annual application of fertilizer at some specified rate, $kg.ha^{-1}.y^{-1}$. From what we already know of the dynamics both of forest ecosystems (Millar 1979) and the way in which trees respond to increased nutrient (Brix 1981), we can predict that accumulation of nutrient in different parts of the system and the increment of foliage amount would not progress uniformly. Of course this does not invalidate such an experiment in itself, but its interpretation could be complex. Rather than adjudging application in terms of rate of fertilizer applied, it might well be appropriate to consider and annual application of fertilizer which is required to raise physiological activity to an increased rate and maintain it at that new rate. For instance, using the bioassay described above for phosphorous, one could experiment to determine the required level of application of phosphorous to maintain the bioassay assessment below a certain value. The important point being that one needs an estimate of rate of functioning. I realize this is a break in tradition from the usual approach to fertilizer experiments, but I suggest this may be necessary if we are to consider how fast we can make forests grow rather than just whether or not we can make them grow a little faster.

In my opinion the principle limitation to the establishment of new, high-yield silvicultural systems designed to feed a particular industrial process will not be biological but industrial

and economic (Rose and Kallstrom 1976). And the relevant measure of productivity will be defined by the process; i.e. whether whole tree fiber is to be used or some form of timber plank is required. The problem with such systems is more likely to be in sustaining them rather than establishing them.

WHAT YIELD CAN BE SUSTAINED AT A SITE?

The concept of sustention has its origins in the principle of a continuous and inexhaustable forest. It covers the multipurpose use of the forest; but as applied specifically to timber yield, its implication is a continuous rather than periodic harvest (Moiseev and Sinitsin 1981, Klemperer 1981) and in straightforward terms it could be judged by the maintenance of a certain standing volume of timber. While this concept of sustention is not relevant to individual stands under intensive, monocyclic management, the implied principle that the forest site should not be degraded by forest operations still is.

The 'second rotation' problem, where the yield of a second rotation on a site is adjudged to be lower than the first is drawing increasing attention. However, there are considerable difficulties in assessing this effect. First, as with determination of site index, the use of the crop itself as a bioassay of conditions is fraught with difficulties. Attempts are made to investigate a possible decline in productivity over successive rotations by comparing site index because this is the measurement most frequently used to assess productivity of the first rotation. In addition to differences in plant genotype and cultural practice (Squire et al 1979) comparisons between rotations may be confounded by long-term (low frequency) changes in the weather which are known to influence tree growth. LaMarche (1974) presented tree-ring width data in which distinct trends of 20-30 years and also 100 years were apparent. Similar trends could result in an observed difference in yield between successive plantations. Such low-frequency variation was also found in an analysis of the long-term winter wheat yields of the Broadbalk winter wheat experiment (Fisher 1924) and which had been established to investigate the effects of repeated cropping. Furthermore, the degree of low frequency weather correlated variation varied between the different manurial treatments of the experiment. In assessing the relative productivity of successive tree plantations on the same site, the effect of long term weather changes could possible be accounted for by conducting ring width and tree height analyses of the final crop trees of the first rotation so enabling comparison of the patterns of growth increment over time. A more comprehensive technique would be to compare the series of annual yields of each plantation against a ring chronology (i.e. LaMarche 1974) established from trees on the same site and which were undisturbed when felling took place. Such a technique may give a separate indication of fluctuations due to weather and the 'rotation' factor. Unfortunately such chronologies are rarely established for commercial species by dendrochronologists.

In my view the difficulties of comparing forest yields over time seriously compromise yield assessments in direct plantation replacement experiments. Long term weather-related trends in yield may be difficult to detect; but we do have sufficient knowledge to know that they should not be ignored. A further difficulty in plantation replacement experiments has been raised by Farrell et al (1981) who worked on the nutrient poor soils of south east Australia. They noted an increase in productivity over the first 5 years in a second rotation replacement plot and attributed this increase in productivity to an increase in soil organic matter in the second rotation. They raised the possibility that a decline in the productivity of the second rotation may be related to a change in cultural practice i.e. burning prior to establishment, and which resulted in differences in soil organic matter. The voluminous literature on the effects that timber extraction methods and site preparation techniques can have on subsequent growth patterns and particularly how the success (or devastating effects) of one technique or another can be markedly influenced by particular weather events, underline the serious difficulties in making comparisons between successive crops. I do not discount these events as factors which influence continuing productivity but note that not all variables which influence tree growth may have equal effect and be readily quantifiable.

I suggest that the crop bioassay approach to the assessment of continuing productivity will have limited value. Some of the logical difficulties in such experiments can be seen in the work of Farrell et al (1981). They went to strenuous efforts to make the second rotation an exact replica of the first, save that organic matter was not burned prior to the establishment of the second and yet this was the factor they invoked to explain the differences. If we wish to determine whether or not yield can be sustained at a site, there appears no alternative but to formulate hypotheses directly in terms of specific growth processes and to monitor at the eco-physiological level. The requirement will then be to assess the degree of management action required to maintain productivity. This can certainly be calculated for forest nutrition (Raisson and Crane 1981), but other factors may be more difficult to assess. A major result from the long-term winter wheat cropping experiment at Broadbalk was an understanding of the population biology of weeds and disease.

CONCLUSION

Repeatedly projections are made that there will be an increasing world-wide demand for timber which must be met from a declining land area available to forestry. This is the principal reason for considering the gap between actual

and potential productivity, the response of systems to increased inputs, and the sustention of high yield. Such global reasoning may seem of little relevance to the individual forest operator; but what I suggest foresters should be interested in is the efficiency of their total operation, and that includes tree growing. At present little attention is paid to a full consideration of the efficiency with which trees are grown because the range of possible inputs to the forest to increase growth rate is restricted by tradition and also because we do not know sufficient about how trees and forests may respond to sustained attempts to increase yield. What foresters particularly require is an understanding of trees and forests as dynamic systems; only in this way can we attempt to assess their response to change.

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FORESTED PLANT ASSOCIATIONS OF THE LOWER NORTHERN SUBALPINE REGIONS OF ALBERTA AND THEIR PRODUCTIVITY RELATIONSHIPS

Satoru Kojima

ABSTRACT: Using a biogeoclimatic approach, six forested plant associations were recognized and described: (1) pine - *Elymus*, representing xeric forest ecosystems; (2) pine - *Shepherdia*, representing subxeric to submesic ecosystems; (3) pine - *Rhododendron*, representing mesic but nutritionally impoverished habitats; (4) spruce/fir - moss, representing mesic ecosystems; (5) pine - alder, representing subhygric but nutritionally enriched habitats; and (6) spruce-willow - *Equisetum*, representing hygric ecosystems.

The pine-alder association showed the highest forest productivity potential and the spruce-willow - *Equisetum* association the lowest. Other associations were interposed between these two associations. A productivity potential map was compiled, based on tree growth characteristics of the associations. The map illustrates the distribution of forest productivity potentials in relation to edaphic conditions.

INTRODUCTION

In Alberta, Canada, on the eastern slopes of the Rocky Mountains, there is a vast extent of forests dominated and characterized by Engelmann spruce (*Picea engelmannii* Parry ex Engelm.) and subalpine fir (*Abies lasiocarpa* (Hook.) Natt.). This type of forest exists within elevational ranges of approximately 1 400 to 2 500 m above sea level near lat. 49° N., 1 600 to 2 400 m above sea level near 50° N., 1 400 to 2 200 m above sea level near 52° N., and 1 300 to 2 000 m above sea level near 54°30' N. This forested area represents a counterpart in Alberta of the Engelmann spruce-subalpine fir biogeoclimatic zone proposed by Krajina (1959, 1965, 1969) in British Columbia.

Because the subalpine zone covers an extensive area between lat. 49° N. and 54°30' N. and from low (*ca.* 1 300 m above sea level) to high (*ca.* 2 500 m above sea level) elevations, it encom-

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passes a great diversity of ecosystematic variation that is expressed in floristic as well as vegetational structure and environmental characteristics. Based on the geographical trends of the variations, Kojima (1980) tentatively proposed four subzonal units within the zone. First, the zone was divided into northern and southern parts based on floristic and vegetational differences. It was further divided into upper and lower units based on some environmental differences as expressed in physiognomy of the forests. The four units, therefore, are the upper northern, lower northern, upper southern, and lower southern units, each of which may be regarded as a subzone of the subalpine zone.

The lower northern subalpine region, as referred to in this article, incorporates the areas of the lower northern subzone of the subalpine zone in Alberta. It develops north of approximately 52° N. latitude and within an elevational range from approximately 1 300 to 1 800 m above sea level. Because the region covers a considerable portion of forest lands in Alberta and is one of the most productive areas in terms of potential forest productivity, it is a vital area from the forestry point of view.

The main objectives of this study include: (1) classification of the forest ecosystems of the lower northern subalpine region of Alberta based on the concept and approach of biogeoclimatic ecosystem classification developed by V. J. Krajina of the University of British Columbia and his students (Kojima 1981a, Krajina 1959, 1965, 1969, 1972); (2) analysis of major environmental factors, especially soils; (3) correlation of vegetational and forest productivity characteristics with those of environment; (4) elucidation of major environmental factors that would critically affect differentiation and development of the forest ecosystems; and (5) provision of baseline information on forest ecosystems of the region to develop ecologically sound forest management practices.

STUDY AREA

The study area includes the eastern slopes of the Rocky Mountains in Alberta, north of ca. lat. 52° N. with an elevational range from ca. 1 300 to 1 800 m above sea level, and a small area of higher elevations in the Swan Hills where the subalpine forests develop as an outlier (fig. 1). These areas incorporate the Upper Foothills Section of the Boreal Forest Region and the lower portions of the East Slopes Rockies Section of the Subalpine Forest Region of Rowe (1972). They are somewhat comparable to the Boreal Uplands and lower portion of the Subalpine Ecoregions of Strong and Leggat (1981).

The climate of the area may be classified as Dfc after Koppen as modified by Trewartha (1958). It is a microthermal climate characterized as follows (table 1): (1) cool humid mountain climate with mean annual temperature ranging from -3 to 2° C and mean annual total precipitation ranging from 450 to 1 000 mm, of which approximately 30 percent falls as snow; (2) low evapotranspiration rate with a potential evapotranspiration ranging from 300 to 450 mm per year, as a result of which practically no water deficit is expected climatically according to Thornthwaite (1948); and (3) relatively high continentality with continental indices (Trewartha 1968) ranging from 36 to 41.

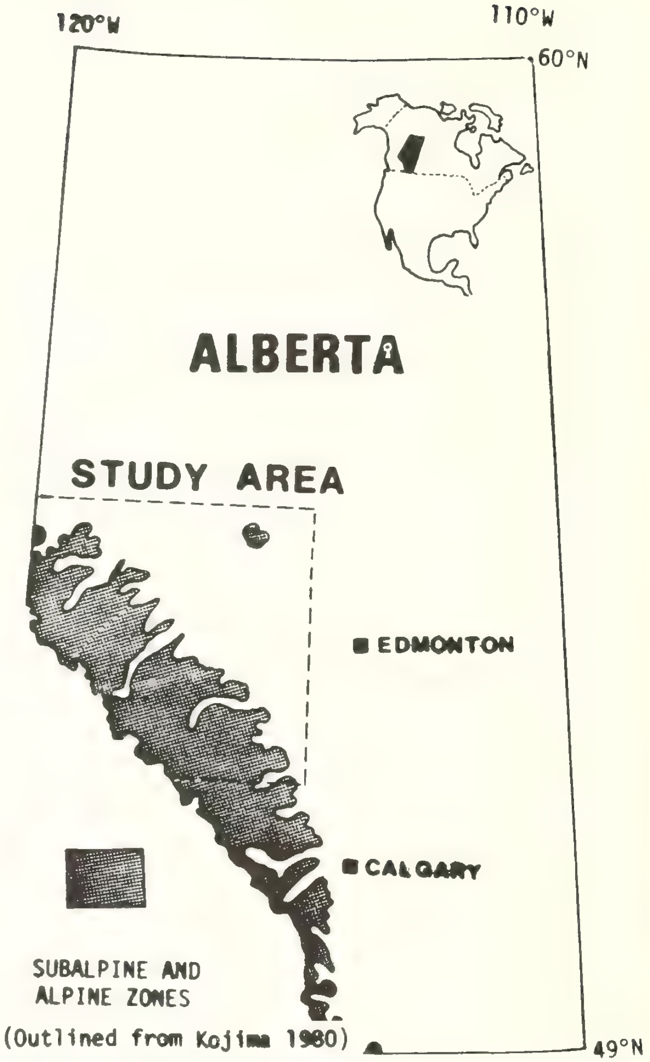

Figure 1.--Geographic range of the subalpine and alpine zones in the study area, Alberta, Canada.

Topography of the area is characteristically mountainous. The forests generally develop on steep terrain, although local topography varies greatly from level to extremely steep. The entire area belongs to the eastern system of the Cordilleran Physiographic Region, particularly to its subdivisions; i.e., the Rocky Mountain Foothills and lower portions of the southern Rocky Mountains (Bostock 1967).

Geology of the area is predominantly sedimentary with some metamorphic, of Precambrian to upper Cretaceous age, and rock types are primarily dolomite, limestone, shale, and sandstone (Canadian Society of Petroleum Geologists 1975;

Table 1--Climatic characteristics of the lower northern subalpine region

Factor	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Temperature (^{o}C)												
Mean monthly	-11.2	-6.4	-3.7	2.1	7.1	10.4	13.4	12.2	8.3	3.9	-3.0	-8.3
Mean maximum	-4.1	1.6	3.5	9.5	14.3	18.1	21.4	20.3	16.1	11.6	3.9	-1.4
Mean minimum	-18.4	-14.4	-11.0	-5.3	-0.3	2.8	5.3	4.1	0.6	-3.9	-9.9	-15.2
Extreme maximum	16.7	18.9	21.2	21.2	26.1	32.2	32.2	31.6	32.2	25.6	18.9	13.9
Extreme minimum	-40.6	-27.8	-30.6	-22.8	-10.0	-4.4	-1.1	-2.8	-11.1	-19.4	-30.0	-39.4
Precipitation (mm)												
Mean total	22	24	46	60	66	115	96	86	50	30	23	21
Mean snowfall	22	24	46	48	16	0	0	0	7	21	22	21

Recorded at Clearwater Research Station, Alberta. Data from "Canadian normals 1941-1970" Vol. 1, 2. Atmospheric Service, Environmental Canada.

Geological Survey of Canada 1969). The dominance of carbonates substantially affected the course of soil development in the area.

Soils of the area cover a wide range of types reflecting a diversity of habitat variation and parent material. A majority of the soils, however, are classed as Brunisols with some occurrences of Podzols and Luvisols (Krumlik et al. 1978, 1979; Twardy and Corns 1980; Walker et al. 1978).

Vegetation of the area is best characterized by closed forests of Engelmann spruce[1/] and subalpine fir in well-matured stands. Seral stands are, however, commonly dominated by even-aged lodgepole pine (*Pinus contorta* Dougl. ex Loud.). Indeed, due to frequent fires, pine stands are widespread. Such stands are in most instances succeeded by spruce-fir stands unless further disturbances take place. Only on extremely well-drained sites will lodgepole pine perpetuate itself, forming a xeric edaphic climax.

As elevation increases, the closed forests tend to become open. Trees become small and stunted, forming clumps with openings between. Such a distribution of trees indicates an area that belongs to the upper subzone of the subalpine zone.

Ground vegetation varies greatly, reflecting site-specific local conditions. In general, *Elymus innovatus* and *Shepherdia canadensis* tend to dominate on well-drained sites, whereas forests seem to be associated with a well-developed moss layer on moderately drained sites with rather depauperate growth of the shrub and herbaceous species. On poorly drained sites, black spruce forests develop that are characterized by well-developed shrub and herb layers of willow and horsetail (*Equisetum* spp.) with high floristic diversity.

[1/]In lower elevations, Engelmann spruce frequently exhibits a hybrid nature with white spruce (*Picea glauca* (Moench) Voss).

METHODS AND PROCEDURES

Analytical Procedures

Basically the concept and approach of biogeoclimatic ecosystem classification were followed. To obtain field data, sample plots, usually 20 m x 20 m, were established. A sample plot is a representation of a forest ecosystem. Plots were subjectively chosen to obtain well-developed and homogeneous sites that reflected ecological characteristics of the forests. In each sample plot, vegetation, physical environment, soil, and tree growth characteristics were analyzed and documented. Description and documentation followed the procedures described in Brooke et al. (1970), Kojima and Krajina (1975), and Kojima and Krumlik (1977).

The description of physical environment included elevation, slope, aspect, topographic position, relief, landform, parent material, and other pertinent information. Vegetation was documented in terms of a species listing (of vascular plants, bryophytes, and lichens), stratification (four main strata and their subdivisions), and evaluation of coverage of each species for each stratum rated by the Domin-Krajina scale (Krajina 1933)

(table 2). Soil description covers those items routinely documented for soil survey and was done according to techniques provided by the Canadian Soil Survey Committee (1977). Soil samples representing different horizons were collected for analyses of the following physical and chemical properties: particle size analysis by the hydrometer method; pH by a combination electrode pH meter for suspensions of soil-to-water ratio of 1:1 for mineral soils and 1:10 for organic soils; organic carbon by Walkley-Black titrimetric wet oxidation method; total nitrogen by the modified Kjeldahl method; cation exchange capacity by the ammonium acetate saturation method; exchangeable cations (Ca, Mg, Na, and K) by atomic absorption spectrophotometry for the leachate after saturating the exchangeable complex with 1.0N ammonium acetate; and available phosphorus by extracting the phosphorus by a 0.5M sodium bicarbonate solution followed by colorimetric determination (882 mμ) by the ascorbic acid method. The soil analyses were conducted mainly in the soil analysis laboratory of the Northern Forest Research Centre, Canadian Forestry Service, Edmonton, Alberta. On the plots, tree growth measurements included diameter at breast height (d.b.h.) and height of all trees over 5 m tall. From some selected trees representing different height classes, core samples were collected with an increment borer for age determination. Total volume of tree stems, mean annual increment, tree density, and site indices of major tree species were calculated from the data.

Table 2--Species significance in Domin-Krajina scale (Krajina 1933)

Class	Description
+	Solitary, very low dominance (covering less than 1%)
1	Seldom, very low dominance (covering 1-2%)
2	Very scattered, low dominance (covering (2-3%)
3	Scattered, low dominance (covering 3-5%)
4	Covering 5-10% of the plot
5	Covering 10-20% of the plot
6	Covering 20-30% of the plot
7	Covering 33-50% of the plot
8	Covering 50-75% of the plot
9	Covering more than 75% but less than 100% of the plot
10	Covering 100% of the plot

Synthetic Procedures

Sample plots representing various forest ecosystems were manually separated into groups based on the provisional determination of ecosystem types in the field. Preliminary vegetation tables were then constructed manually. A computerized cluster analysis was conducted concurrently to group the plots on the basis of vegetational similarities (Ksd) originally proposed by Sorensen (1948) as modified by Dahl (1956). After the preliminary groupings, Klinka's vegetation tabulation program (Klinka and Phelps 1979) was used to construct the final vegetation tables and to calculate necessary statistics such as average species significance and constancy for each species. The vegetation tables were further checked and changes of plot sequence were made when needed.

When all the adjustments were completed, each vegetation table was accepted as representing a plant association. A plant association (as defined by Krajina 1960) is the smallest unit discriminable vegetationally as well as environmentally. Its typification is based on sample plots that possess similar structure and occur in similar habitats.

When the final vegetation tables were prepared, characteristic species combinations were determined for each plant association. They consisted of three categories of plants (modified from Kojima 1971): (1) constant dominant species (CD)--those species having a high constancy with presence class more than IV; (2) constant species (C)--those species having a high constancy but low dominancy with an average species significance less than 4; and (3) important companion species (I)--species not belonging to either of the above categories but more or less exclusively associated with a certain plant association, hence characterizing it.

After the vegetation data analyses were completed, environmental and tree growth data were processed. Data were assembled and grouped by plant association. Calculations of some statistics, such as means, ranges, and standard deviations, were made for each association. Based on the environmental characteristics, especially those of soils, edatopic positions of the plant associations were determined. An edatopic position is a position projected in an edatopic grid matrix proposed and extensively used by Krajina (1969, 1972) and his students. The edatopic grid matrix is constructed with two parameters; i.e., hygrotope and trophotope. Hygrotope represents the magnitude of moisture availability to plants in a particular site, which is rated in nine classes. Trophotope represents the magnitude of total availability to plants of nutrients, primarily bivalent cations, which is rated in six classes. An interaction of the two parameters makes 54 possible combinations, each of which can accommodate one type of ecosystem (fig. 2). Assessment of the edatope (hygrotope and trophotope) was made subjectively by integrating factors that affect the availability of moisture and

HYGROTOPE \ TROPHOTOPE	A OLIGOTROPHIC (Very poor)	B SUBMESOTROPHIC (Poor)	C MESOTROPHIC (Medium)	D PERMESOTROPHIC (Rich)	E SUBEUTROPHIC to EUTROPHIC (Very rich)	F HYPEREUTROPHIC (Excessively rich)
VERY XERIC (Excessively drained) 0						
XERIC (Very rapidly drained) 1						
SUBXERIC (Rapidly drained) 2						
SUBMESIC (Well drained) 3						
MESIC (Moderately well drained) 4						
SUBHYGRIC (Imperfectly drained) 5						
HYGRIC (Poorly drained) 6						
SUBHYDRIC (Very poorly drained) 7						
HYDRIC (Water standing) 8						

Figure 2.--Edatopic grid matrix.

nutrients. Major factors taken into consideration include topographic position, presence or absence of seepage, physical and chemical properties of the soils, and responses of plants in terms of growth or vigor. The grading of an association is relative to other associations that occur within the same biogeoclimatic zone or subzone. When the edatopic position of each plant association was determined, it was projected diagramatically in the edatopic grid matrix to show its edatopic characteristics and relative position.

Table 3--List of forested plant associations recognized in the study area

	Name of association	Short name
1	Pinus contorta - Juniperus communis - Elymus innovatus	Pine - Elymus
2	Pinus contorta - Shepherdia canadensis - moss	Pine - Shepherdia
3	Pinus contorta - Rhododendron albiflorum - Rubus pedatus	Pine - Rhododendron
4	Picea engelmannii/Abies lasiocarpa - Vaccinium membranaceum - moss	Spruce/fir - moss
5	Pinus contorta - Alnus crispa - Arnica cordifolia	Pine - alder
6	Picea mariana - Salix spp. - Equisetum spp.	Spruce - Equisetum

RESULTS

Six plant associations were recognized in the study area, based on 68 selected plots (table 3). These associations represent only the forested ecosystems in the area: the number of associations would be greatly increased by consideration of non-forested ecosystems.

Vegetation structure and characteristic species groups are presented in table 4. In the table, those species framed in rectangles indicate characteristic species for the six associations. Detailed descriptions of the six plant associations is provided in Kojima (1981b). Soil characteristics are summarized in table 5 and fig. 3. Brief descriptions of the six associations are presented below.

1. Pine - Elymus association (=Pinus contorta - Juniperus communis - Elymus innovatus association)

This association represents xeric to subxeric ecosystems of the area. It usually develops on predominantly south-facing slopes and on well-drained habitats with coarse substrates. It tends to prefer calcareous parent materials. Vegetation of this association is characterized by the presence of such species as Elymus innovatus, Juniperus communis var. nana, Shepherdia canadensis, Arnica cordifolia, Hedysarum alpinum, Fragaria virginiana, and Pyrola secunda. The tree layer consists mostly of even-aged lodgepole pine occasionally mixed with white spruce (Picea glauca), Engelmann spruce, and hybrids of the two. The shrub layer is dominated by Juniperus communis var. nana with Shepherdia canadensis also characteristic. The herb layer is well developed, and dominated and characterized by Elymus innovatus, followed by Zygadenus elegans, and Hedysarum alpinum. The moss layer is weakly developed although Hylocomium splendens, Pleurozium schreberi, and Cladonia coccifera show relatively high dominance.

Soils are generally coarse textured and are derived mostly from glacial till and some colluvium. The L-H horizon is characteristically thin. Base status is very high. In fact, this association shows the highest base saturation of the six associations studied. Acidity is also low. The C:N ratio is medium ranged. Amount of available phosophorus is medium in relation to other associations. Soils are classified as Orthic Gray Luvisol, Orthic Eutric Brunisol, Orthic Dystric Brunisol, and Orthic Regosol.

2. Pine - Shepherdia association (=Pinus contorta - Shepherdia canadensis - moss association)

This association represents subxeric to submesic ecosystems. It develops on well-drained to moderately drained habitats of gently sloping land forms, mostly of glacial origin. Slopes tend to be southerly. Vegetationally, this association is characterized by the presence of such species as Shepherdia canadensis, Elymus innovatus, Vaccinium caespitosum, Arctostaphylos uva-ursi, Carex richardsonii, Lathyrus ochroleucus, Maianthemum canadense, Zygadenus elegans, Arnica cordifolia, Linnaea borealis, Vaccinium vitis-idaea, and Cornus canadensis. The tree layer consists mainly of lodgepole pine. White spruce and Engelmann spruce occur frequently in the subordinate tree layer. The shrub layer is well developed and overwhelmingly dominated by Shepherdia canadensis, followed by Rosa acicularis, Juniperus communis var. nana, and Spiraea lucida. The moderate herb layer includes Vaccinium vitis-idaea, Arctostaphylos uva-ursi, Elymus innovatus, Linnaea borealis, Arnica cordifolia, Lathyrus ochroleucus, and Zygadenus elegans. The moss layer is also moderately developed and dominated by Pleurozium schreberi and to a lesser extent by Hylocomium splendens, Ptilium crista-castrensis, and Peltigera aphthosa.

Table 4--A synopsis of species groups characterizing the plant associations (the Arabic numerals represent average species significance in Domin-Krajina scale and Roman numerals represent constancy class)

Species / Association	Pine - Elymus	Pine - Shepherdia	Pine - Rhododendron	Spruce/fir - moss	Pine - alder	Spruce - willow - Equisetum
Number of plots representing	8	2	10	28	8	12
Trees:						
Pinus contorta	7.IV	8.V	7.V	6.IV	7.V	1.I
Picea glauca	4.II	3.III	-	+/I	+.I	2.I
Populus tremuloides	-	3.III	-	-	+.II	-
Picea engelmannii	+.III	-	3.II	4.II	-	4.III
Abies lasiocarpa	+.II	-	1.IV	3.IV	+.III	+.III
Picea mariana	-	2.III	3.II	3.III	+.II	6.V
Species groups characterizing plant associations:						
Hedysarum alpinum	+.III	-	-	-	-	-
Juniperus communis var. nana	1.V	4.III	-	-	+.I	-
Fragaria virginiana	+.IV	+.III	-	+.I	+.II	+.III
Elymus innovatus	7.V	4.V	-	+.I	4.II	1.I
Shepherdia canadensis	3.V	6.V	-	+.I	+.II	+.I
Zygadenus elegans	+.IV	+.V	-	-	+.I	-
Vaccinium caespitosum	2.II	3.III	+.I	+.I	+.I	+.I
Arctostaphylos uva-ursi	1.II	5.V	-	-	2.I	-
Carex richardsonii	+.I	+.III	-	-	-	-
Lathyrus ochroleucus	+.II	+.V	-	-	+.I	-
Maianthemum canadense	-	+.III	-	+.I	+.I	-
Rhododendron albiflorum	-	-	7.V	+.II	-	-
Empetrum nigrum	-	-	4.IV	1.II	-	+.II
Arnica latifolia	-	-	+.III	1.I	+.I	-
Lycopodium annotinum	-	-	1.V	1.IV	+.III	+.I
Vaccinium membranaceum	+.I	-	6.V	5.V	2.III	1.I
Ledum groenlandicum	+.II	4.III	4.III	5.IV	2.II	3.IV
Rubus pedatus	-	-	4.IV	5.IV	1.III	1.I
Streptopus roseus	+.I	-	+.II	+.III	+.III	+.I
Epilobium angustifolium	+.III	+.III	+.II	+.II	3.V	+.III
Alnus crispa	-	-	-	+.I	7.V	-
Spiraea lucida	+.II	+.III	-	+.I	2.V	-
Pyrola asarifolia	+.I	-	-	+.I	1.III	+.I
Rubus pubescens	-	-	-	-	I.IV	+.II
Calamagrostis canadensis	-	-	+.I	1.II	4.IV	1.V
Petasites palmatus	-	-	+.I	+.III	+.IV	1.V
Ribes lacustre	+.II	-	-	+.II	+.II	+.III
Lonicera involucrata	-	-	-	+.I	+.II	4.IV
Salix barclayii	-	-	-	-	-	5.III
Ribes triste	-	-	-	+.I	+.II	+.III
Achillea millefolium	-	-	-	+.I	+.I	+.V
Aster ciliolatus	-	-	-	-	+.I	+.III
Carex disperma	1.I	-	-	-	-	3.IV
Carex vaginanta	-	-	-	+.I	-	4.V
Delphinium glaucum	+.I	-	-	+.I	+.I	+.III
Deschampsia caespitosa	-	-	-	-	3.II	+.III
Equisetum arvense	-	-	+.I	+.I	1.II	5.V
Equiseum pratense	-	-	-	+.I	+.I	5.III

cont:

Table 4 cont.

Species / Association	Pine - Elymus	Pine - Shepherdia	Pine - Rhododendron	Spruce/fir - moss	Pine - alder	Spruce - willow - Equisetum
Number of plots representing	8	2	10	28	8	12
Trees:						
Equisetum scirpoides	-	-	-	+.I	+.I	3.IV
Equisetum sylvaticum	+.I	-	+.II	+.III	1.III	5.IV
Listera cordata	-	-	+.I	+.II	+.II	+.III
Mertensia paniculata	1.II	-	-	+.II	+.II	2.V
Galium boreale	+.III	-	-	+.I	+.II	+.IV
Mitella nuda	+.II	-	-	+.II	2.II	2.V
Rubus acaulis	-	-	-	-	1.II	+.IV
Rubus chamaemorus	-	-	-	-	-	2.III
Senecio triangularis	-	-	-	-	-	+.IV
Anemone richardsonii	-	-	-	-	-	1.III
Geum rivale	-	-	-	-	-	+.III
Listera borealis	-	-	-	-	-	+.III
Species widely occurring with no special affiliation with any associations:						
Arnica cordifolia	+.IV	+.V	2.II	1.II	4.IV	+.I
Cornus canadensis	+.III	1.III	4.V	5.V	5.V	4.IV
Linnaea borealis	4.V	3.V	+.III	4.V	3.V	2.III
Pyrola secunda	+.V	+.III	+.III	+.IV	1.IV	+.III
Vaccinium vitis-idaea	3.II	5.V	3.IV	5.V	4.V	4.V
Major bryophytes and lichens:						
Hylocomium splendens	5.IV	5.IV	5.V	7.V	6.V	7.V
Pleurozium schreberi	4.IV	6.V	7.V	6.V	5.V	5.V
Ptilium crista-castrensis	2.II	+.V	5.V	6.V	5.V	5.V
Peltigera aphthosa	2.IV	1.V	2.V	2.IV	+.V	+.V
Aulacomnium palustre	-	-	+.I	+.I	+.I	5.IV

Soils are moderately coarse textured and derived from glacial till. Horizon development is rather weak. Base status and pH are medium ranged. The C:N ratio is characteristically low in this association. The amount of available phosphorus is low to moderate. Soils are classified as Orthic Dystric Brunisol.

3. Pine - Rhododendron association (=Pinus contorta - Rhododendron albiflorum - Rubus pedatus association)

This association develops in submesic to mesic habitats of poor nutritional status. It occurs on gentle hillsides, but tends to be more common at higher elevations (up to ca. 2 000 m above sea level) where snow tends to accumulate. This association is characterized by such species as Rhododendron albiflorum, Empetrum nigrum, Arnica cordifolia, Lycopodium annotinum, Vaccinium membranaceum, Ledum groenlandicum, Rubus pedatus, Cornus canadensis, and Vaccinium vitis-idaea. The tree layer consists predominantly of lodgepole pine with frequent occurrences of black spruce (Picea mariana (Mill.) B.S.P.) and subalpine fir. The shrub layer is well developed and overwhelmingly dominated by Rhododendron albiflorum. Development of the herb layer is moderate. Major species of the layer include those species listed above. In general, the number of species occurring in this association is much higher than in the preceding two associations. The moss layer is very well developed with Hylocomium splendens, Pleurozium schreberi, and Ptilium crista-castrensis as major species. Lichens such as Peltigera aphthosa, Cladonia coniocraea, and C. gonecha are common in this layer.

Soils are moderately fine textured and are derived mainly from glacial till. Base status and pH of the soils is characteristically low. This association shows the lowest pH of the six associations. The C:N ratio varies over a broad range. The amount of available phosphorus is the highest of the six associations. Soils are classified as Degraded Drystric Brunisol and Orthic Dystric Brunisol.

Table 5--Means of soil analyses for six associations

Soil factor / Horizon	Pine - Elymus	Pine - Shepherdia	Pine - Rhododendron	Spruce/fir - moss	Pine - alder	Spruce - willow - Equisetum
pH:						
L-H	5.0	4.6	3.3	3.8	4.1	5.6
A	4.9	4.9	3.7	3.8	4.7	5.4
B	5.5	4.8	3.9	4.6	4.9	6.1
C	7.2	4.9	4.5	5.2	5.9	6.0
Organic carbon (%):						
L-H	21.5	25.1	35.3	35.2	39.3	37.7
A	0.9	0.3	2.4	2.1	2.4	10.1
B	1.1	0.6	1.1	1.6	1.0	2.4
C	1.3	0.3	1.0	1.0	1.4	5.6
Total nitrogen (%):						
L-H	0.56	0.93	0.89	0.99	1.37	1.27
A	0.05	0.04	0.11	0.13	0.14	0.64
B	0.07	0.06	0.07	0.19	0.08	0.11
C	0.09	0.05	0.06	0.06	0.09	0.20
C/N ratio:						
L-H	36.3	27.0	40.0	36.5	32.5	30.0
A	18.5	7.5	20.7	15.3	16.4	17.3
B	14.0	9.3	15.4	14.4	13.0	21.4
C	14.2	5.5	14.1	13.4	15.3	24.4
Cation exchange capacity (m.eq./100 g):						
L-H	65.3	58.7	93.5	92.7	92.3	140.0
A	11.5	9.4	17.9	20.3	18.9	72.5
B	18.8	12.4	18.6	19.2	16.5	22.6
C	13.6	18.0	20.1	17.7	24.0	29.6

cont:

Table 5 cont.

Soil factor / Horizon	Pine - Elymus	Pine - Shepherdia	Pine - Rhododendron	Spruce/fir - moss	Pine - alder	Spruce - willow - Equisetum
	Association					
Calcium (m.eq./100 g):						
L-H	38.13	27.44	7.93	23.13	30.65	94.60
A	6.88	5.61	3.42	3.91	7.80	52.57
B	12.33	5.42	2.24	6.69	9.57	19.69
C	21.57	10.32	9.30	12.19	18.30	23.72
Magnesium (m.eq./100 g):						
L-H	8.93	7.40	3.38	5.96	9.87	17.72
A	2.09	2.14	1.16	1.26	2.61	8.74
B	5.65	2.23	0.86	2.23	3.05	4.46
C	4.65	4.61	2.62	3.19	5.02	4.56
Sodium (m.eq./100 g):						
L-H	0.04	0.07	0.24	0.34	0.14	0.24
A	0.02	0.02	0.03	0.08	0.04	0.11
B	0.03	0.03	0.04	0.09	0.04	0.03
C	0.02	0.03	0.05	0.09	0.08	0.08
Potassium (m.eq./100 g):						
L-H	1.41	2.08	2.44	2.53	2.01	0.96
A	0.28	0.26	0.21	0.30	0.27	0.39
B	0.36	0.24	0.14	0.24	0.39	0.14
C	0.14	0.31	0.23	0.28	0.32	0.23
Base saturation (%):						
L-H	88	64	16	37	49	80
A	78	86	24	26	52	77
B	96	64	22	49	77	107
C	193	85	59	96	96	97
Available phosphorus (ppm):						
L-H	87.9	49.0	103.7	79.6	60.2	22.1
A	15.6	5.3	16.4	9.3	9.3	5.9
B	14.7	8.5	18.2	11.4	7.0	2.6
C	6.1	6.2	13.5	7.3	6.1	3.8

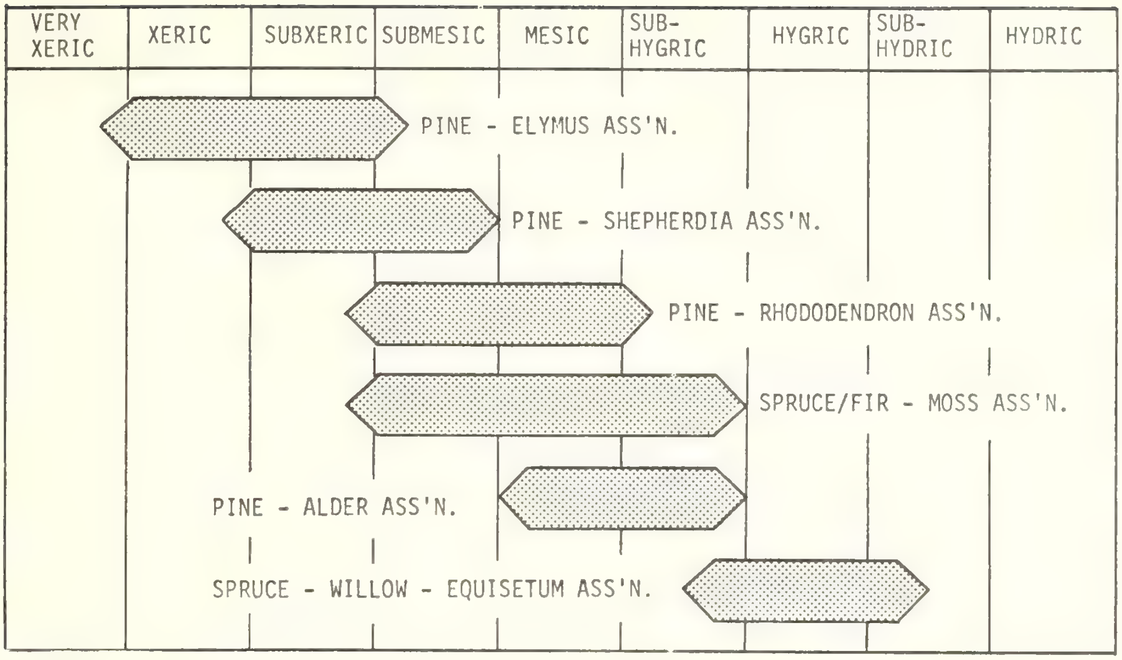

Figure 3.--Hygrotopic sequence of the associations.

4. Spruce/fir - moss association (=Pinus engelmannii/Abies lasiocarpa - Vaccinium membranaceum - moss association)

This association represents mesic to drier portions of subhygric ecosystems. It is the most widespread forested ecosystem in the area and covers a wide range of land forms. It is characterized by such species as Vaccinium membranaceum, Ledum groenlandicum, Rubus pedatus, Streptopus roseus, Cornus canadensis, Linnaea borealis, Pyrola secunda, and Vaccinium vitis-idaea. The tree layer consists of a mixture of Engelmann spruce, subalpine fir, and black spruce. Lodgepole pine occurs as a remnant of the early successional stages in many instances. The shrub and herb layers are weakly developed. In contrast, the moss layer is characteristically well developed and forms a thick and dense moss carpet.

Soils are of moderate to fine texture and are derived from various kinds of parent material, although mostly from glacial till. Base status and pH of the soils is low. The C:N ratio is variable and shows largest values in the L-H horizons with a decreasing trend with depth. Available phosphorus is relatively high. Soils are mostly Eluviated Eutric Brunisol, and Orthic Dystric Brunisol with some Orthic Gray Luvisol, Orthic Eutric Brunisol, and Orthic Gleysol.

Because this association occurs over a wide range of parent material and land forms, it may be divided into two subassociations based on vegetational structures which reflect some of the environmental differences. They are the Ledum groenlandicum and typical associations. The former occurs on more depauperate soils while the latter occurs on comparatively more fertile soils.

5. Pine - alder association (=Pinus contorta - Alnus crispa - Arnica cordifolia association)

This association represents mesic to subhygric ecosystems with fertile soils. It occurs fairly commonly throughout the study area on gentle slopes mostly of morainal land forms. This association is characterized by the presence of such species as Alnus crispa, Spiraea lucida, Rubus pedatus, Streptopus roseus, Epilobium angustifolium, Aster conspicuus, Calamagrostis canadensis, Pyrola secunda, P. asarifolia, Rubus pubescens, Arnica cordifolia, Cornus canadensis, Linnaea borealis, and Vaccinium vitis-idaea. The well-developed tree layer is dominated by lodgepole pine, followed by Engelmann spruce and subalpine fir. The shrub stratum has a dense tall shrub layer dominated by Alnus crispa. The herb layer is moderately developed and is dominated by Cornus canadensis, accompanied by Arnica cordifolia, Linnaea borealis, Pyrola secunda, Calamagrostis canadensis, and Pyrola asarifolia. The moss layer is moderate with major constituents of Hylocomium splendens, Dicranum fuscescens, Polytrichum juniperinum, Peltigera aphthosa, Cladonia gracilis, and Ptilium crista-castrensis.

Soils are generally fine-textured and mainly derived from glacial till or rarely from lacustrine sediments. Ground water may be present at a depth of 20 to 30 cm from the surface although it is usually much deeper. Base status of the soils is high and pH values are also fairly high in this association. The soils characteristically show large amounts of nitrogen. In fact, nitrogen levels are the highest in this association out of the six studied. Amount of available phosphorus is in the medium range. Soils are classified mostly as Orthic Dystric Brunisols and occasionally Orthic Gray Luvisols.

Table 6--Tree growth characteristics of six plant associations (indicating means for the associations)

	Association and number of plots it represents					
	Pine - Elymus	Pine - Shepherdia	Pine - Rhododendron	Spruce/fir - moss	Pine - alder	Spruce - willow - Equisetum
	8	2	10	28	8	12
Parameters						
Total volume of tree stems (m^3/ha)	301.1	264.7	297.9	338.8	414.1	274.8
Stand age (year)	134	92	122	122	131	154
Mean annual increment (m^3/ha)	2.40	2.66	2.18	2.43	3.34	1.65
Average height (m)	14.8	15.1	13.2	14.8	20.8	13.8
Number of trees/ha	1773	1116	1799	1852	742	1835
Volume/tree (m^3)	0.17	0.24	0.17	0.18	0.56	0.15
Site index (m/70 years)						
lodgepole pine	14.2	15.0	11.3	13.0	18.2	10.3
Engelmann spruce	14.5	---	8.0	9.1	13.0	8.0
black spruce	---	---	10.5	10.6	---	9.4
subalpine fir	---	---	8.0	6.6	18.0	---

5. Pine - alder association (=Pinus contorta - Alnus crispa - Arnica cordifolia association)

This association represents mesic to subhygric ecosystems with fertile soils. It occurs fairly commonly throughout the study area on gentle slopes mostly of morainal land forms. This association is characterized by the presence of such species as Alnus crispa, Spiraea lucida, Rubus pedatus, Streptopus roseus, Epilobium angustifolium, Aster conspicuus, Calamagrostis canadensis, Pyrola secunda, P. asarifolia, Rubus pubescens, Arnica cordifolia, Cornus canadensis, Linnaea borealis, and Vaccinium vitis-idaea. The well-developed tree layer is dominated by lodgepole pine, followed by Engelmann spruce and subalpine fir. The shrub stratum has a dense tall shrub layer dominated by Alnus crispa. The herb layer is moderately developed and is dominated by Cornus canadensis, accompanied by Arnica cordifolia, Linnaea borealis, Pyrola secunda, Calamagrostis canadensis, and Pyrola asarifolia. The moss layer is moderate with major constituents of Hylocomium splendens, Dicranum fuscescens, Polytrichum juniperinum, Peltigera aphthosa, Cladonia gracilis, and Ptilium crista-castrensis.

Soils are generally fine-textured and mainly derived from glacial till or rarely from lacustrine sediments. Ground water may be present at a depth of 20 to 30 cm from the surface although it is usually much deeper. Base status of the soils is high and pH values are also fairly high in this association. The soils characteristically show large amounts of nitrogen. In fact, nitrogen levels are the highest in this association out of the six studied. Amount of available phosphorus is in the medium range. Soils are classified mostly as Orthic Dystric Brunisols and occasionally Orthic Gray Luvisols.

6. Spruce - willow - Equisetum association (=Picea mariana - Salix spp. - Equisetum spp. association)

This association represents hygric to subhygric ecosystems. It develops on lower slopes and in depressions where water collects. This association is characterized by the presence of such species as Salix barclayii, S. myrtillifolia, S. planifolia, Ribes lacustre, R. triste, Lonicera involucrata, Achillea millefolium, Aster ciliolatus, Petasites palmatus, Carex disperma, C. vaginata, Delphinium glaucum, Deschampsia caespitosa, Equisetum arvense, E. pratense, E. scirpoides, E. sylvaticum, Listera cordata, Mertensia paniculata, Galium boreale, Mitella nuda, Rubus acaulis, R. chamaemorus, Senecio triangularis, Anemone richardsonii, Geum rivale, Listera borealis, Cornus canadensis, and Vaccin-

ium *vitis-idaea*. The tree layer consists predominantly of black spruce. White spruce is rarely present and subalpine fir is occasional. At lower elevations, tamarack (*Larix laricina* (Du Roi) K. Koch) is a rare constituent. The well-developed shrub layer is dominated by willows (*Salix barclayii*, *S. farrae*, *S. myrtillifolia*, and *S. planifolia*). The herb layer is well developed and floristically well diversified as indicated by the above-mentioned species. The moderate moss layer is dominated by *Hylocomium splendens* followed by *Peltigera aphthosa* and *Ptilium crista-castrensis*, but occurrence of *Aulacomnium palustre*, *Tomenthypnum nitens*, and *Sphagnum warnstorffii* is a unique feature. The latter are thought to reflect poorly drained and fertile habitat conditions.

Soils are fine- to moderately fine-textured. Parent materials are glacial till and lacustrine sediments. Base status and pH are generally high. The amount of nitrogen is also high, but C:N ratio is variable. The water table is shallow in this association, having been recorded at depths from 18 cm below ground surface to ground surface. Most soils show gleying due to poor aeration in the mineral horizons. Amount of available phosphorus is rather low. Soils were mostly Orthic Gleysol, Rego Gleysol, and Rego Humic Gleysol with some Organic soils.

Tree Growth Characteristics

Of the six plant associations studied, the pine - alder association supports the highest productivity for it shows the highest values in total volume of tree stems per hectare, average tree height, mean annual increment, and site indices of lodgepole pine and subalpine fir (table 6). The moss association appears to be second: It is median in such values as total volume of tree stems per hectare, average tree height, and average volume per tree. Despite the high base status of soils, the spruce-willow-*Equisetum* association has low forest productivity. It exhibits the lowest values for total tree volume per hectare, average height of trees, mean annual increment, average volume per tree, and site indices of lodgepole pine, Engelmann spruce, and black spruce. The pine-*Elymus* association shows relatively good forest productivity as the site index of Engelmann spruce is highest in this association. Growth of lodgepole pine is also rapid in this association. The pine-*Shepherdia* association seems to have a fairly high productive potential as it shows the second highest values in average height of trees and mean annual increment as well as site index of lodgepole pine. The pine-*Rhododendron* association is the lowest in forest productivity. It has the lowest average tree height and the second lowest mean annual increment and average volume per tree. Site indices of tree species are generally low in this association.

DISCUSSION

Sequence of the Associations

The hygrotope is essentially a gradient of moisture availability to plants. It is assessed based on topographic position, soil texture, field moisture of soil, and growth response of plants.

The hygrotope status of each association was assessed and placed in sequence (fig. 4). The pine-*Elymus* association, which occurs on upper slopes or on well-drained soils, appears on the driest portion of the hygrotope scale. The spruce-willow-*Equisetum* association, which develops in valley bottoms or in concave topography, is positioned on the wetter portion of the scale. Other associations are arranged between these two associations.

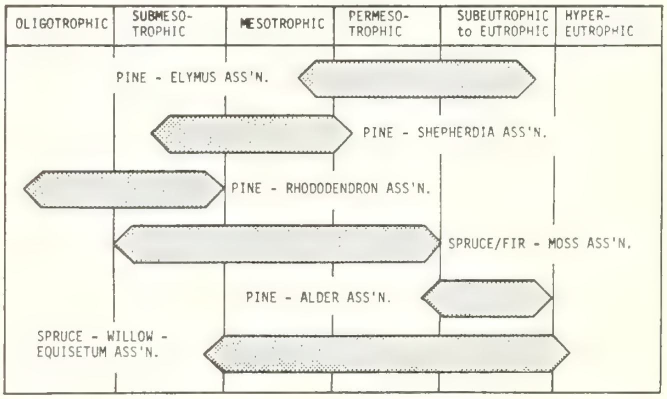

Figure 4.--Trophotopic sequence of the associations.

Trophotope is essentially a gradient of nutrient availability to plants, primarily of bivalent cations and nitrogen. The trophotopic status of each association is based on topographic position, kind of parent material, chemical characteristics of soil, presence or absence of seepage water, and growth response of plants.

The trophotope sequence of the six associations is quite different from that of the hygrotopic sequence (fig. 5). In general, ecosystems developed on drier and wetter sites have a high trophotope and those occurring on mesic sites have a low trophotope. Thus, the pine-*Rhododendron* association shows the lowest trophotopic status and the spruce/fir-moss association is the second lowest. On the other hand, the pine-*Elymus* association and the spruce-willow-*Equisetum* association show the highest trophotopic status. The pine-*Shepherdia* association and the pine-alder association are between these extremes.

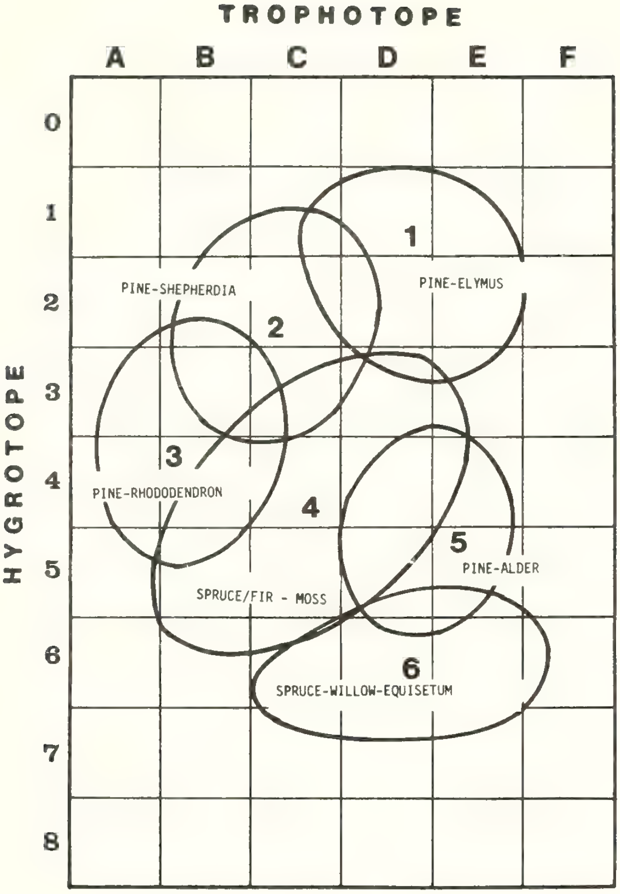

Figure 5.--Edatopic position of the associations.

The overall trend of relationships between hygrotope and trophotope is somewhat different from that recorded for coastal British Columbia. Hygrotope and trophotope generally show a positive correlation in the forest ecosystems of coastal British Columbia (Kojima 1971, Kojima and Krajina 1975). In Alberta, these two edatopic characters are not necessarily positively correlated. This difference may be due to different climatic regimes.

In coastal British Columbia, the climate is typically maritime--mild and humid with large amounts of precipitation, prolonged cloudy periods, small diurnal and seasonal fluctuations of temperature, and little water deficiency. Under such a climate, a high rate of soil leaching results in the removal of bivalent cations and subsequent acidification of the soils. This tendency is more pronounced on sites of upper slopes and ridge crests that lack seepage effects. On the other hand, sites in valley bottoms at the bases of slopes are enriched with bivalent cations in seepage waters. Thus, the habitats have positive correlations between hygrotope and trophotope.

In Alberta, the climate is typically continental; that is, characteristically drier with much larger diurnal and seasonal fluctuations of temperature. Greater water deficits are expected than in British Columbia due to higher rates of potential evapotranspiration. Precipitation may be insufficient to remove the basic cations, and leaching of soils would be extremely slow or absent. This would be particularly true for upper slopes and ridge crests that have relatively high insolation levels and wind exposure. Sites on upper slopes would not be subjected to strong leaching. On mesic sites on middle slopes, however, the rate of potential evapotranspiration may be slightly lower than that on the upper slopes because of less wind exposure and better development of forest canopy which would lower the soil temperature. In such habitats, leaching might remove at least some basic cations. This may explain the lower base status and pH values in mesic associations such as the pine-Rhododendron and the spruce/fir-moss. On sites of slope bases and valley bottoms, basic cations would be supplied by seepage. Enrichment of such sites would increase the base status and pH. This would explain the contrast in trophotopic and hygrotopic relationships between coastal British Columbia and Alberta.

The hygrotopic and trophotopic characteristics of the six associations are summarized in composite form in an edatopic grid matrix (fig. 6).

Forest Productivity Relations

Tree growth characteristics and soil characteristics of the six associations are also shown in table 6 and figure 7, respectively.

The pine-alder association supports the highest forest productivity potentials. The high productivity of the association seems related to the high nutritional status of soils, particularly: (1) high levels of nitrogen, presumably due to active symbiotic nitrogen fixation in the rhizospheres of alders; (2) reasonably high levels of bases; (3) ample supplies of potassium since this association shows the highest levels of potassium in the mineral horizons as well as high levels in the organic horizons; and (4) moderate drainage.

In contrast, the spruce-willow-Equisetum association has rather low productive potential despite the nutrient-rich soils. In fact, base and nitrogen levels are the second highest of the six associations. Drainage is very poor, however, which seems to result in lowered tree growth.

The pine-Elymus association that develops on xeric habitats has soils that are quite rich in bases. Base saturation of the soils is highest of the six associations. Excessive drainage and soil desiccation appear to result in lowered forest productivity potential.

The pine-Shepherdia association and the spruce/fir-moss association appear average in potential forest productivity. The former association occurs in excessively drained subxeric habitats resulting in low moisture availability. Low moisture and moderate base levels result in moderate forest productivity. In the latter association, moisture availability is medium but

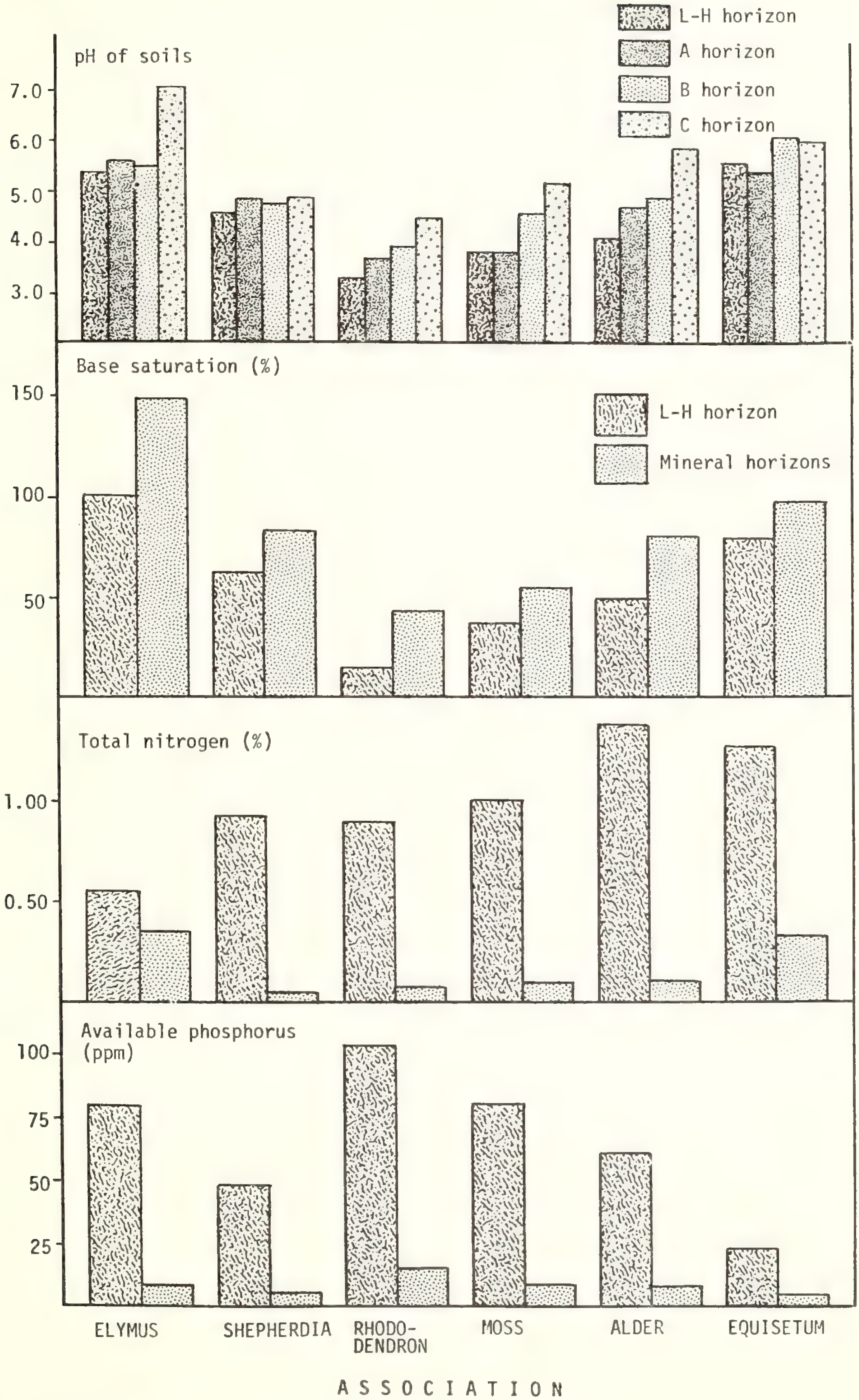

Figure 6.--Soil characteristics of the associations.

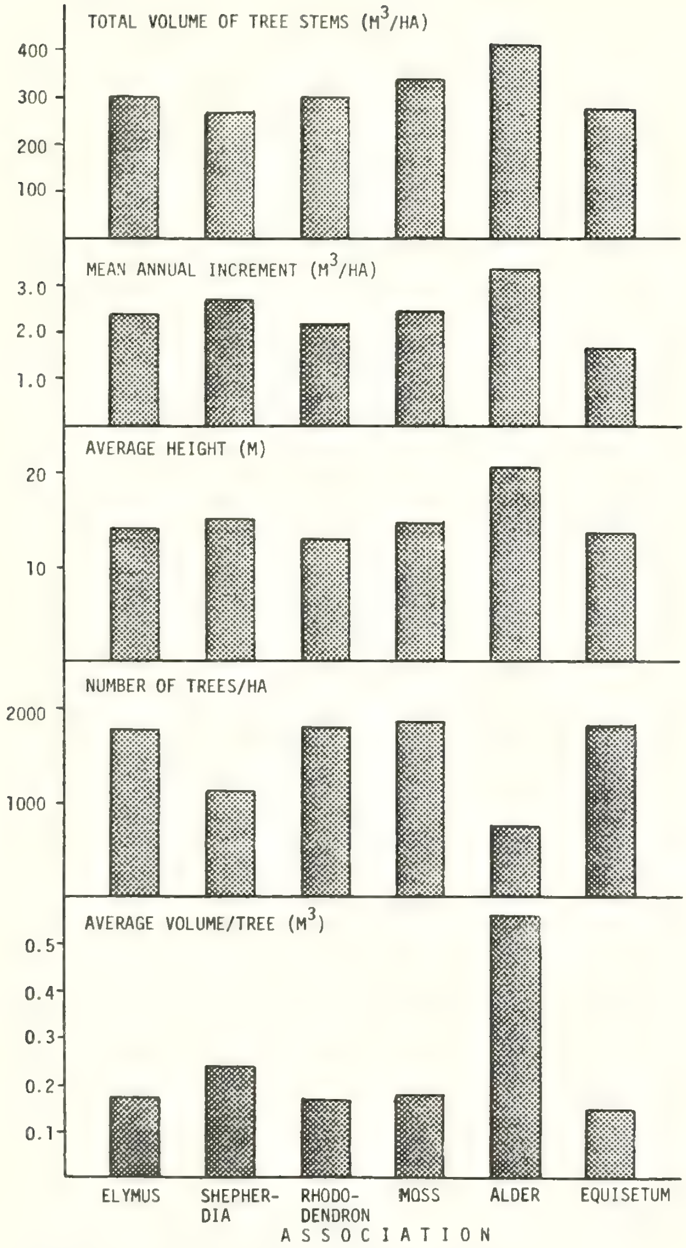

Figure 7.--Tree growth characteristics of the associations.

base levels are rather low, presumably due to comparatively higher rates of leaching. This lowers the productivity resulting in a medium class productivity potential.

The pine-Rhododendron association has low productivity. It occurs on mesic habitats but its nutritional status is very low. In fact, base saturation as well as pH values are lowest of the six associations. The low productivity may be the result of low base status that is, in turn, a result of higher rates of leaching in this association.

To compare the forest productivity potential of the six associations, a productivity index was prepared based on selected tree growth characteristics. The characteristics included total volume of tree stems per hectare, mean annual increment, average height of canopy-forming trees, and average volume per tree (table 7). These are considered to be indicators of forest productivity potential of the associations. Tree growth characteristics were first qualitatively rated in three broad classes: high, medium, and low. The ratings were then quantitatively expressed, with 3 points assigned for "high," 2 points for "medium," and 1 point for "low." Points were summed for each association, divided by the maximum possible points and multiplied by 100. The index thus ranges from 100 for the case in which all the tree growth characteristics were rated as "high" to 33.3 where all characteristics were rated as "low." Numerous tree growth parameters can be utilized for comparison of associations on a uniform scale using this method.

The productivity indices of the six associations are listed in table 5 along with mensurational variables rated in three broad classes mentioned previously. The pine-alder association has the highest productivity potential with an index of 100. The pine-Elymus, the pine-Shepherdia, and the spruce/fir-moss associations follow with an index of 58. The pine-Rhododendron association is next with an index of 50 and the spruce-willow-Equisetum association has the lowest productivity potential with an index of 33.3.

The productivity indices of the six associations were overlaid on the composite edatopic grid matrix. Using the productivity indices of the associations as projected in the edatopic grid matrix, a productivity potential map in relation to edatopic position of the associations was constructed (fig. 8). Distribution of the forest productivity potentials is indicated in relation to the edatopic characteristics. Three isolines in the map border the three productivity potential classes. This map profiles the productive potentialities of forested plant associations in the lower northern subalpine regions of Alberta.

SUMMARY

Forest ecosystems of the lower northern subalpine regions of Alberta were classified using a biogeoclimatic approach. Six forested plant associations were recognized and briefly described: (1) pine-Elymus association representing xeric forest ecosystems of the area; (2) pine-Shepherdia association representing subxeric to submesic forest ecosystems; (3) pine-Rhododendron association representing mesic but nutritionally impoverished habitats; (4) spruce/fir-moss association representing mesic forest ecosystems; (5) pine-alder association representing forests on subhygric but nutritionally enriched habitats; and (6) spruce-willow-Equisetum association representing hygric ecosystems of the area. Their edatopic positions were determined based on the environmental characteristics and growth responses of plants. The edatopic positions were then projected in an edatopic grid matrix to show their relative positions and relationships.

Table 7--Productivity indices of the six associations

Factor	Pine - Elymus	Pine - Shepherdia	Pine - Rhododendron	Spruce/fir - moss	Pine - alder	Spruce - willow - Equisetum
	Association					
Tree growth characteristics:						
Total volume/ha	medium	low	medium	medium	high	low
Mean annual increment	medium	medium	low	medium	high	low
Average height	medium	medium	low	medium	high	low
Volume/individual tree	low	medium	medium	low	high	low
Productivity points[1/]	7	7	6	7	12	4
Productivity index[2/]	58	58	50	58	100	33

[1/]The quantitative estimates shown here are summations of the three broad classes (low, medium, high) assigned to four tree growth characteristic parameters, in which 3 points were assigned for "high," 2 points for "medium," and 1 point for "low."

[2/]Productivity index was calculated by dividing the productivity points by possible maximum number (12 points in this case) and multiplied by 100.

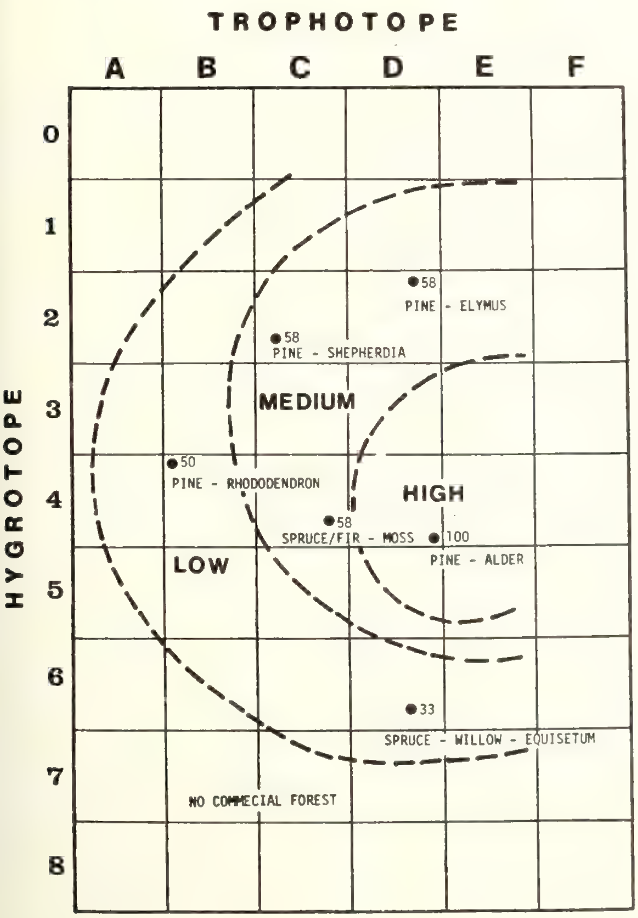

Figure 8.--Productivity potential map of the lower northern subalpine region of Alberta.

It became apparent that the pine-alder association showed the highest forest productivity potential and the spruce-willow-Equisetum association showed the lowest potential. Other associations were interposed between the above two associations. The pine-alder association seemed to have developed on moderately well-drained sites with ample supplies of nutrients and with a particularly abundant supply of nitrogen, presumably due to symbiotic nitrogen fixation. An interaction of these variables has resulted in such a high productivity potential. In the case of the spruce-willow-Equisetum association, which was the lowest in forest productivity, poorly drained and water-saturated soils would have caused the low productivity despite the fact that base status in the association was very high. Other associations demonstrated moderate productivity potentials as they developed under medium-ranged environmental conditions.

A productivity potential map was compiled, based on tree growth characteristics of the six associations. The map illustrated the distribution of forest productivity potentials in relation to edaphic conditions. Such a map will serve as a useful guide to predict where possible high or low forest productivity is expected in relation to edaphic conditions and in relation to forested plants associations of the lower northern subalpine regions of Alberta.

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FOREST SITE PRODUCTIVITY ASSESSMENT: MEETING NEEDS IN MASSACHUSETTS[1]

D. L. Mader, W. P. MacConnell
J. C. Mawson, and J. F. O'Keefe[2]

ABSTRACT: An increased need for site productivity assessment in Massachusetts has been caused by a trend to more intensive forest management as a result of new markets, increased stumpage values, and land tax classification regulations. Small-sized ownerships, site and species diversity, and lack of large wood-using industries require that an extremely flexible, convenient, and accessible site classification system be developed if it is to be widely adopted and useful. A prototype system based on physiographic region, elevation, slope, aspect, and soil group has been devised and is being tested and refined to meet the dual needs for generalized site classification and prime forest land classification and mapping for Massachusetts.

INTRODUCTION

The effects of soil and other site factors on the growth and productivity of forests in Massachusetts has been one of our prime research interests for over 25 years. Intensive soil-site studies have been made of red pine (*Pinus resinosa* Ait.), white pine (*Pinus strobus* L.), sugar maple (*Acer saccharum* Marsh.), and northern red oak (*Quercus rubrum* L.) (Mader and Owen 1961, Hoyle and Mader 1964, Mader 1976, Mader and Thompson 1969, and Schweigel 1980).

The resulting information has been helpful in clarifying the importance of different site factors for the various species, and several effective site prediction equations have been developed. These studies have not been fully satisfactory, however, because they have not provided simple, easy-to-use systems for general dissemination. Recognition of this deficiency has called for re-examination of the needs for site information in the southern New England region, systems that could best meet those needs, and how the systems can best be packaged for potential users.

Forests in southern New England present a combination of characteristics that pose problems for the development and use of site classification/evaluation systems. Almost all of the forest land is in small, private holdings. There are virtually no large wood-using industries or large industrial or Federal landholdings typical of the South and West. In the past, the primary interest of forest-landowners was not in wood production. Lack of demand for timber, coupled with the high proportion of unmerchantable small material, discouraged intensive forest management. Natural regeneration

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was abundant and landowners were satisfied with minimal management of the resulting diverse stands. Incentives to use site information in land acquisition or to determine the most valuable species to favor on various sites were small. Systems to analyze forest soils, interpret the results, and convey that information to landowners or managers were essentially nonexistent. Although Massachusetts has both soil testing services and an extension service capable of reaching landowners to deliver site information, there has been little demand for a forest-site information system.

Two questions arose. Could we develop a site quality information system? And would the effort be justified? Fundamental changes are taking place that are increasing the demand for such information. New fuelwood markets have opened up widespread profitable opportunities for more intensive management. Increased transportation costs and inflation have improved markets for native softwoods and increased incentives for management and the need for site information. High stumpage prices for quality hardwoods have had a similar effect. Tax policies in Massachusetts strongly favor more intensive management. Properly managed forest land is eligible for special classification to reduce land taxes, offset by a yield tax which is deferred until products are harvested. High land values and mandated 100 percent valuation for assessment purposes have made such classification a necessity for many owners in order to retain their land for forestry purposes. An approved forest management plan and actual forest management and harvesting operations are required in order to maintain such a classification. Much of the intensive management is being directed by consulting foresters capable of utilizing site data.

Federal and State programs to provide management assistance to small private landowners are developing productivity criteria to target funds to stands with reasonable growth potential. State resource inventory and planning agencies need site-related information to provide a data base on forest growth potential. Overall the need for good site productivity information is clear and fully justifies an active research effort.

CRITERIA FOR A SITE-INFORMATION SYSTEM FOR MASSACHUSETTS

Several characteristics critical to a successful site system for small, diverse forest ownerships of the State have been identified:

1. Ease of use
2. Readily accessible to all potential users
3. Applicable to various tree species
4. Negligible expense to the manager
5. Flexible for use at various levels of information needs
6. Capable of refinement for increased accuracy, if needed.

Present site information sources do not fully meet these criteria. The soil survey reports of the U.S.D.A. Soil Conservation Service (SCS) contain site information but it often lacks precision for specific sites (Carmean 1975). These soil survey reports are lacking for much of Massachusetts. Both factors have limited the use of soil surveys. Site prediction equations have had little use because of unfamiliarity and the absence of analytical and interpretive service. Site index is the only commonly used forest productivity measure and it is included in most management plans. Yield tables needed to properly interpret site values are not available in a convenient and accurate form for many species.

To meet the criteria listed above we have initiated a research program to develop a map-based site-information system and to investigate how to utilize available soil survey information for estimating forest site productivity.

A site-typing system on a map base was chosen as the best alternative for ease of use and accessibility. The goal was to develop a site classification system based on geographic zones, topographic features, climate, and soils with site-type delineation made on aerial photographs with the aid of soil maps and U.S. Geological Survey (U.S.G.S.) topographic maps. Minimum area for delineation was set at 5 acres.

A further dimension was added to this effort in 1981 when a project to classify, identify and map the prime forest lands in Massachusetts was initiated at the request of the Massachusetts Department of Environmental Management (DEM). The two projects were integrated because of the potential advantages of a single system to be implemented by the DEM, SCS, and the University of Massachusetts to meet several levels of need.

THE PROTOTYPE SYSTEM

Drawing on previous work, particularly the Hill's System and the Biophysical Land Classification work in Canada (Hills 1952, Hills and Pierpoint 1960, Jurdant et al. 1975), and the Weyerhaeuser system (Steinbrenner 1975), we designed a prototype system to meet the needs for both prime forest-land classification and site classification. This system is being evaluated.

The proposed site classification system consists of five consecutive levels of separations. The first separation is by the major geographic provinces in the State; i.e., the eastern coastal zone, the central upland, the Connecticut Valley, and the Berkshire Hills. These zones will separate major differences in climate and geology. The second subdividion is by 500-foot elevation classes to differentiate any major differences in local climate such as greater rainfall or lower temperatures at higher elevations. The third separation is by four slope classes corresponding to groups of SCS slope classes. Slopes up to 8 percent were combined because they are insufficient to have a major effect on solar radiation input, erosion, or moisture regimes. In the interest of simplicity, the number of additional classes were limited to three--

9-25 percent, 24-45 percent, and over 45 percent--which should provide adequate differentiation. The fourth level of subdivision is according to aspect and separates the northeast (NEQ), southwest (SWQ), and northwest/southeast (NWQ/SEQ) quadrants for aspect. A recent study in Massachusetts (Schweigel 1980) showed solar radiation index (SRI), which is a function of slope and aspect, to be an important factor in site quality for red oak. Several previous studies (Lloyd and Lemmon 1970) also support the generally accepted belief that northeast aspects have greater productivity in this region because of a more favorable solar energy/soil moisture balance. The four slope classes and three aspect groups should provide sufficient energy regime classes and minimize the complexity of the system.

The final level of separation in the sequence is based on soil groups, of which there are seven. These correspond quite closely to the Woodland Suitability Groups developed by the SCS with some modification on the basis of previous site studies. These classes will be refined as more data are accumulated. The system allows 490 discrete units of classification for the State, too many for practical use. As data accumulates, units will be combined into fewer classes for an effective yet workable system.

The system is designed to be as objective as possible, based primarily on available map-based information. After geographic provinces are defined they can be easily located on U.S.G.S. topographic sheets, which show elevation, slope, and aspect. With the aid of aerial photographs and soil maps, the site units can be delineated. If the soils in an area are not mapped, the photo-interpreter will infer the soil grouping from topographic features or forest types in comparable areas. Mapping of soils in Massachusetts will be complete in the near future so that soils information will soon be available for all areas. Separation by soils was made the final step in the sequence to allow further refinement if desired. Site prediction could be adjusted by detailed soil examination or testing for physical or chemical parameters. Part of the current research program is the study of selected soil series and groups of similar soils to ascertain soil factors contributing to variation in site productivity. Field measurements or laboratory tests can then be developed to improve site prediction.

A mylar overlay with the site types delineated and identified will be produced to scale to be used over the 7.5-minute U.S.G.S. topographic sheet. Further transparencies or paper copies can then be easily made for distribution to users. Woodlots or stands will be easily located on the maps by owners or foresters. The site quality information will improve judgements as to land value, silvicultural opportunities, growth rates, species suitability, etc. The overlay system is an inexpensive, flexible one suitable for a wide range of users. A resource-data base on acreages of forest types or sites by potential productivity can be derived for regional economic and resource planning.

PRIME FOREST LANDS MAPPING PROGRAM

The Massachusetts Department of Environmental Management contracted for a prime forest-lands classification and mapping project in 1981. The objectives were to define the prime forest lands in the State, develop a system to classify them, and test the system on a pilot basis by mapping four counties.

Definition of prime forest land in Massachusetts is difficult because of the great diversity of commercial species and the large differences in volume growth and value among them. The national standard for prime forest land, established by the USDA Forest Service, is a potential mean annual net increment of $6.0 m^3$ ha.yr/(85 cu. ft./acre.yr) at the age of culmination. Using the growth of the major softwood, white pine, as a standard, most of the land in Massachusetts would fall in the prime category. If the major hardwood, red oak, were used, very little of the land would classify as prime. Most of the land can and does grow both species, so it is difficult to devise a logical system to assign a specific species to a site for classification purposes. In addition, if the national standard were used without further separation in the prime category, the information would be of value only on a very broad basis because of the unidentified large variation in productivity in the site categories.

We devised a refined system using three categories of prime land with a dual productivity rating system based on both white pine and red oak. This system is shown in Table 1. The classes provide a practical separation of the relative productivity of the forest lands of the State for landowners, foresters, tax assessors, and others. The dual rating basis permits classification of the land within the national system on any desired basis. The resource potential can be evaluated by either rating basis for various planning and economic objectives, yet the prime categories can be aggregated for a national resource data base consistent with other States.

SITE CLASSIFICATION AND PRIME LANDS MAPPING PROCEDURE

Sampling, testing, and refinement of the proposed site classification system were not done prior to initiating the mapping of prime forest lands because of time constraints.

Ideally, sites are to be classified by the system, assigned to categories, and placed in the proper prime land category according to site productivity values. The map units are to be given both a site class and prime land notation on the transparent overlay prepared at U.S.G.S. map scale. The overlay can be used easily and be readily and inexpensively reproduced in whole or in part for landowners or foresters.

A slightly different and more subjective classification of prime forest lands is being used. On an interim basis for the four county pilot

Table 1. Prime forest (timber) land classification system proposed for Massachusetts based on white pine and red oak.

	Class	White pine Volume[2] m³/ha	White pine Volume[2] ft³/acre	White pine SI[1] 50	Northern red oak Volume[2] m³/ha	Northern red oak Volume[2] ft³/acre	Northern red oak SI[1] 50
I.	1 (Prime I) -	>10.9	>155	>70	>3.9	>55	>65
II.	2 (Prime II) -	8.4-10.8	120-154	60-69	3.2-3.8	45-54	60-64
III.	3 (Prime III) -	6.0-8.3	85-119	50-59	2.8-3.1	40-44	55-59
IV.	S (Statewide importance) -	4.6-5.9	65-84	45-49	2.5-2.7	35-39	50-54
V.	L (Local importance) -	<4.6	<65	<45	< 2.7	<35	<50
VI.	U (Unique)[3]	N/A	N/A	N/A	N/A	N/A	N/A

[1]Site index values are at age 50 (SI_{50}).
[2]Cubic volumes are potential average productivity per year at age of culmination of mean annual increment.
[3]Presently limited to cedar swamps.

project, sites are examined on 1:80,000 aerial photographs. First, the area is identified by soil type from a soil map and assigned to one of nine soil groups, representing gradations of prime class ratings. These groups were developed on the basis of SCS site data and previous site information. Then using topographic information on slope, aspect, slope position, and stand characteristics, the prime class rating is adjusted up or down based on whether the site is above or below average according to the judgement of the photo interpreters. Development of more objective criteria over time is anticipated.

Initial Verification

The initial pilot prime forest-lands mapping project is to map prime timber lands in four counties of Massachusetts. The four counties contain the equivalent of about 50 U.S.G.S. quadrangle sheets. Two to 3 days are required to classify one quadrangle sheet on the photographs. The equivalent of 21 have been completed. The transfer process from 1:80,000 photographs to 1:25,000 scale transparent overlays for the U.S.G.S. sheets takes about 2 days per quadrangle, inking and lettering about another day.

Verification of the classification is done by direct field measurements of site index on selected sites. Of 24 check plots, 12 have been correctly classified, 9 have been one class low, and 3 have been two classes low. These results are considered to be reasonably good since most are less than one 10-foot site class in error and they are consistently low. Accuracy should improve with continued experience and refinement.

CONCLUSIONS

Site productivity information in Massachusetts, a State with many, small, individual ownerships needs to be in an easily used and readily accessible form. The need for such information is increasing rapidly because of factors favoring intensive management. A map-based system for site classification based on soil and topographic features has been devised. A modification of the system is being tested for prime timber-lands classification. Preliminary results from a four-county pilot project are encouraging. The system should be efficient, cost effective, and meet the needs both for site information for landowners and resource information for planners and others. Plans are to prepare transparent overlays showing site/prime land units for the entire State at U.S.G.S. topographic sheet scale.

The Massachusetts DEM, the SCS, and the University of Massachusetts will cooperate in making the information and materials available to users.

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ECOLOGICAL FOREST SITE CLASSIFICATION AND MAPPING IN THE MCCORMICK EXPERIMENTAL FOREST, UPPER MICHIGAN

K. S. Pregitzer, B. V. Barnes, T. A. Spies, and V. Spooner

ABSTRACT: A team approach was used to develop a multifactor ecosystem classification in the Cyrus H. McCormick Experimental Forest, in the north-central Upper Peninsula of Michigan. Unique combinations of physiography, soils, and vegetation were used in the field to systematically classify and map the 7000-ha tract. Groups of ground-flora species based on similar habitat conditions, termed ecological species groups, enabled those mapping the sites to more easily distinguish different edaphic conditions. The entire Experimental Forest was subdivided into biologically equivalent ecosystems--termed site units. Ecosystem boundaries were mapped at a scale of 1:15,840.

Each ecosystem occupied a characteristic topographic position within the landscape. Individual ecosystems differed significantly in many of their biophysical properties such as slope, aspect, soil texture, soil drainage, and soil fertility.

The ecosystems were characterized by distinctive potential overstory and ground-flora compositions. Certain ecological species groups were found to be effective indicators of soil moisture, texture, pH, and total nitrogen. Placing the emphasis of ecosystem classification on the biophysical structuring of the local landscape greatly facilitated understanding functional relations between plants and environment.

INTRODUCTION

Identifying and classifying forested land according to its biological potential is an important aspect of forest management. Forest managers need to know which factors determine productivity (growth and yield), and they need to be able to reliably predict productivity of management units. Silvicultural and economic decisions also depend on identifying the potential of a site, for example, predicting response to the application of fertilizer and determining the impacts of intensive harvest on site nutrient balance (Silkworth and Grigal 1982). According to Carmean (1975, 1977), the most critical need in the area of forest-site classification is development of indirect methods of estimating site quality over the entire landscape regardless of the condition or kind of vegetal cover.

Numerous single-factor methods of ecosystem description are available for classification. Vegetation as an indicator of site potential is emphasized in the habitat typing method (Cajander 1926, 1949; Daubenmire and Daubenmire 1968; Pfister et al. 1977; Pfister and Arno 1980). Many studies have clearly demonstrated that plants can be effectively used to indicate environmental conditions and site quality (Ellenberg 1950, 1952, 1953; Waring and Major 1964; Daubenmire 1961; Zobel et al. 1976; Orloci and Stanek 1979; Westman 1981; Pregitzer and Barnes 1982).

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Physiography and soil factors have also been effectively used as single-factor systems to classify the forest or predict tree growth (Rowe 1962; Carmean 1961, 1977, 1979; Leak 1978; Hodgkins et al. 1979). Another approach to land classification is a component system (Corliss 1974; Buttery 1978; Henderson et al. 1978; Bailey 1980; Radford et al. 1981).

Beyond ecosystem description, it is important at the local level to ask what factors can best be used to stratify the landscape into units of equivalent biological potential? We believe that multifactor methods of forest-site classification are advantageous when compared to single-factor or component methods. Multifactor methods integrate physiography, soils, and vegetation to classify and map forest potential.

An ecological approach to multifactor site classification is desirable because it stresses functional dependence among ecosystem components (Barnes et al. 1982). Single-factor methods of site classification often fail to provide all the necessary information. A classification utilizing only vegetation does not develop a detailed sense of physiography and soils. Do sites receive, transport, or store groundwater? Are soils sensitive to erosion or depletion of nutrient reserves? Is fertilization an alternative? On the other hand, if only topographic and soil information is used to build an ecosystem classification, one cannot appreciate how these factors relate to one another and compensate for one another to affect the composition, dynamics, and productivity of plant species.

Component systems integrate single-factor climatic, soil, and vegetation classifications to formulate taxonomic units. They differ from multifactor methods in that integration of factors is conducted after the landscape has been classified according to single-factor methods. According to Bailey's (1980) description of "site," the local unit of biological potential, it appears that our concept of the local unit of land capability is close to his.

Our objective is to describe the results of applying an ecological approach to multifactor site classification.

STUDY AREA

The Cyrus H. McCormick Experimental Forest, Ottawa National Forest, occupies about 7000 ha on a conspicuous bedrock feature known as the Michigamme Highlands in north-central Upper Peninsula of Michigan. Lake Superior lies 22 km due north and the city of Marquette lies 50 km southwest.

Climate is continental with a growing season of approximately 100 days. Precipitation averages 790 mm annually and is evenly distributed throughout the year, with an average of 272 cm of snowfall. Average daily temperatures are about 18.5°C in July and -10°C in January.

Bedrock is chiefly gneiss and appears to conform to the description of Compeau Creek Gneiss (Gair and Thaden 1968). The area was deglaciated about 10,500 BP (Segerstrom 1964; Farrand 1969). A detailed palynological study of forest composition in and around the McCormick Experimental Forest was presented by Brubaker (1975).

Soils have formed in relatively coarse-textured fluvioglacial sediments. The depth of the sediments varies considerably over the area and exposed bedrock is common at the higher elevations. Upland soils of the study area are Entisols, Inceptisols, and Spodosols. They range in texture from gravelly coarse sand through loam. Mineral soils are acid and low in exchangeable bases. Lowland soils are Histosols and range in pH from about 4.1 to 7.0.

The study area is within the Superior upland section of the Hemlock-White Pine-Northern Hardwood Region (Braun 1950). Many stands are essentially pristine. Acer saccharum Marsh. is dominant on deep, well-drained soils of loamy sand and finer textures. Other overstory species occasionally found on these soils are Acer rubrum L., Betula alleghaniensis Britton, Tilia americana L., and Tsuga canadensis (L.) Carr. Pinus strobus L. and Quercus rubra L. are characteristic of rocky exposed sites. Mineral soils influenced by groundwater support a diverse overstory of the above species plus Picea glauca (Moench) Voss and Abies balsamea (L.) Mill. Extremely acid organic soils are dominated by Picea mariana (Mill.) B.S.P. More basic organic soils support the most diverse overstory including many of the above species plus Thuja occidentalis L. and Fraxinus nigra Marsh.

METHODS

We applied a multifactor site classification method modeled after work conducted in Baden-Württemberg, West Germany (Schlenker 1964). Each ecosystem type, known as a site unit, was defined in the field by a distinctive combination of physiography, soils, and vegetation. The vegetation of each site unit was named for the dominant overstory species and the most characteristic ecological species group.

An overview of the multifactor method of site classification is presented by Barnes et al. (1982). A brief discussion of methodology follows.

The field sampling design was stratified-random. A reconnaissance technique was developed. Topographic, soil, and vegetal information was collected during the systematic reconnaissance of the study area. The information was used to create a field classification and to stratify the landscape into different ecosystems. Plots were then established randomly within each ecosystem.

During the 1978 and 1979 field seasons, 108 plots were sampled. Plots were 15 x 30 m in size and each plot was subdivided into three 5 x 30 m

subplots. Plot sampling included observations on physiography, soils, and vegetation (Pregitzer 1981; Pregitzer and Barnes 1982; Pregitzer et al. 1983).

Topographic position was recorded for each plot: (1) rocky knoll or rocky ridgetop; (2) high plateau, above the influence of groundwater; (3) ridgetop with soil mantle; (4) upper slope; (5) midslope; (6) footslope; (7) protected valley; (8) low plateau, influenced by groundwater; and (9) depression. Additional physiographic information included: (1) percent slope measured from a 30.5-m base line, (2) aspect to the nearest degree, (3) depth to water table, (4) average depth to bedrock determined at three points, and (5) notes on parent material and probable mode of deposition of parent material.

Soil was described from a pit (depth 150 cm or bedrock) near the center subplot. Soil samples were collected from the center cf all mineral horizons for laboratory analysis. Bulk density was estimated according to Pregitzer and Barnes (1982).

Soil laboratory analyses included particle-size distribution, organic matter, pH, and macronutrients by standard techniques (Pregitzer and Barnes 1982; Pregitzer et al. 1983). Soil information was summarized by profile.

All ground-flora species in the entire plot were recorded; species within the center 5- x 30-m subplot were then intensively sampled including records of relative frequency, abundance, and percentage canopy coverage (Pregitzer and Barnes 1982).

An important feature of the Baden-Württemberg method of ecosystem classification is the use of ecological species groups to help classify and map site units. Each ecological species group is composed of several plant species that, presumably, because of similar environmental requirements or tolerances, indicate certain site-factor complexes; e.g., soil moisture or soil acidity levels. Assignation to a group was determined by examination of synthesis tables and by the results of numerical clustering and multivariate statistical procedures (Pregitzer and Barnes 1982). Groups are named for a characteristic species and comprise 1 to 14 species. In this paper, we report the mean percentage of maximum canopy coverage, which was determined by summing the coverage classes of all the species in a group and dividing by the maximum sum attained for the group in any plot.

Several numerical and statistical techniques were used during data analysis. Analysis of variance was used to test for significant differences among average physiographic and soil properties. Principal component analysis (Morrison 1976) was used to summarize the variation in physiographic and soil variables. Empirical distribution functions (Conover 1971) were used to study the distribution of ecological species groups over environmental gradients.

Site units of the Experimental Forest were mapped according to procedures outlined by Barnes et al. (1982). Site mappers worked as a team, and each team member was trained to interpret ecosystems based on a combination of physiography, soils, and vegetation. Each site mapper, therefore, had at least basic training in forest ecology, botany, soils, and geology.

THE MCCORMICK CLASSIFICATION

Twenty-one ecosystems were classified and mapped (table 1). Each site unit occurred in characteristic topographic positions; and there was a strong correlation among topography, soils, and vegetation. Site units within the local classification are arranged hierarchically according to drainage and physiographic position. These two factors are useful in integrating soil and vegetal differences among site units (Damman 1979). The ecological comparison outlined below among the four driest site units occurring on deep soils illustrates the application and resolution of the multifactor method.

RESULTS

Comparison of the Four Driest Site Units on Deep Soils

Site Unit 1.--Site Unit 1 is dominated by *Pinus banksiana* Lamb. and total basal area and average canopy heights are lowest of the four units (table 2). High canopy coverage of the *Vaccinium*, *Pteridium*, and *Deschampsia* ecological species groups easily distinguish this ecosystem from others (table 3).

Topography is level and very uniform (fig. 1). The soil is exceptionally well sorted; 84 percent of the particle size distribution occurs in the medium and fine sand fractions (table 2).

Soils in Site Unit 6 are nearly identical in texture and degree of sorting. However, the physiographic location of these site units is very different. Site Unit 6 occurs on steep southerly slopes in contrast to the extensive level topography of Unit 1.

Soil texture is uniform throughout the profile and the hydraulic conductivity of these soils is extremely high. Site Units 1 and 6 contain lower levels of soil organic matter than the hardwood dominated ecosystems. Low levels of soil organic matter lead to the low levels of total soil nitrogen (table 2).

Site Unit 1 can be distinguished from Site Unit 2, which also occurs on level topography, by lower amounts of organic matter in the upper B2 horizon (lack of distinct B2h), and lack of obvious strata of different textures. It can be easily distinguished from Site Unit 4 by lower amounts of organic matter and topographic position (fig. 1). Only physiography, as discussed above, distinguishes Site Units 1 and 6; however,

Table 1--Classification of site units of the natural area of the McCormick Experimental Forest.

Dryland Site Units

I. Deep soils (bedrock below 100 cm)
  A. Level to gently sloping terrain (usually 0-5 percent)
    1. Excessively drained sand; jack pine/Vaccinium[1]
    2. Somewhat excessively drained sand and gravel; sugar maple/Maianthemum
    3. Somewhat poorly drained sand; maple--yellow birch--conifer/Clintonia
  B. Moderately to steeply sloping terrain (usually >5 to <30 percent)
    4. Well-drained loamy sand; sugar maple/Gymnocarpium
    5. Moderately well-drained sandy loam on northerly aspects; sugar maple/Viola
    6. Excessively drained sand on steep southerly aspects, white pine-hardwoods/Maianthemum

II. Shallow soils (bedrock within 50 cm)
    7. Somewhat excessively drained fine sandy loam on exposed sites; maple-red oak/Maianthemum
    8. Well- to moderately well-drained sandy loam on protected sites; red maple-yellow birch-conifer/Clintonia
    9. Excessively drained sandy loam on southerly aspects; white pine/Cladonia

III. Other physiographic units
    10. Exposed rocky ridges; white pine-red oak-hardwoods/Polygonum
    11. Small protected valleys and stream flats; sugar maple-conifer/Circaea
    12. Lake and stream borders; conifer-hardwood/Myrica
    13. Rocky streamsides; conifer-hardwoods/Aralia
    14. Flood plain with alluvial loamy soil; sugar maple/Botrychium
    15. Coarse outwash plain; conifer/Caldonia

Wetland Site Units

    16. Open bog; Chamaedaphne/Sphagnum
    17. Very infertile swamp on peat (black spruce swamp); black spruce/Ledum
    18. Infertile swamp on peat (acid hardwood-conifer swamp); hardwood-conifer/Osmunda
    19. Fertile swamp on muck (circum-neutral hardwood-conifer/Circaea)
    20. Open meadow and marsh; sweet gale-sedge
    21. Streamside alder on muck; speckled alder/Thalictrum

[1]Although not occurring in the natural area, this nearby ecosystem of the Yellow Dog Plains was included because it provides the xeric extreme for comparison.

the ecological species groups easily distinguish these two ecosystems (table 3).

Site Unit 2.--Acer saccharum strongly dominates the moderately well to somewhat excessively drained deep soils of Site Unit 2. It is the driest ecosystem dominated by Acer saccharum and represents the transition between conifer and hardwood dominated forests (table 2). Other hardwood species are scattered in the overstory of Site Unit 2 (table 2), and Pinus strobus stumps are also frequently encountered. The presettlement overstory contained a considerable component of Pinus strobus. The overstory is relatively open and trees are short and of poor vigor.

The ecosystem can be easily distinguished from the conifer-dominated ecosystems (Site Units 1 and 6) by high coverages of the Maianthemum, Dryopteris, Oryzopsis, and Streptopus groups, and absence of the Vaccinium, Cladonia, and Deschampsia groups (table 3).

The most important edaphic difference between Site Units 1 and 6 vs. 2 is soil texture. The weighted-average soil textures presented in table 2 show no large differences in texture. The soil profiles of Site Unit 2, however, are characterized by two or more distinct strata differing widely in texture as opposed to the homogeneous sediments of Site Units 1 and 6. Layers of coarse sand and gravel are common (fig. 1). Alternating bands of sand and gravel slow water infiltration (Brady 1974). In addition, the upper 30 cm of Site Unit 2 soils contain 10-15 percent more silt than those of Units 1 and 6. These subtle textural differences provide this ecosystem with more available soil moisture compared to Units 1 and 6.

Levels of soil organic matter and total nitrogen are higher in Unit 2 soils than those of Site Units 1 and 6 (table 2). This is especially true in the upper B2 horizon. The development of a dark brown band of organically enriched soil in the upper B2 is characteristic of Site Units 2 and 4. The development of a B2h horizon appears

Table 2--Summary of overstory composition and selected edaphic factors for the four driest site units occurring on deep soils of the McCormick Experimental Forest[2]

Species	Site unit			
	1	2	4	6
	basal area (m^2 - ha^{-1})			
Acer rubrum (L.) Mill.	-	3.4	1.5	5.0
A. saccharum Marsh.	-	24.3	29.7	1.1
Betula alleghaniensis Britton	-	4.2	5.0	2.4
B. papyrifera Marsh.	-	-	-	0.5
Ostrya virginiana (Mill.) K. Koch	-	-	0.3	-
Pinus banksiana Lamb.	18.6	-	-	-
Pinus strobus L.	-	-	-	40.0
Prunus serotina Ehrh.	0.1	0.8	-	-
Quercus rubra L.	-	1.8	-	-
Tilia americana L.	-	-	0.3	-
Tsuga canadensis (L.) Carr	-	-	2.0	9.8
Total Basal Area	18.7	33.5	38.8	58.8
Average Canopy Height (m)	17.5	21.9	23.8	28.3
Edaphic Factor				
Percent medium sand[3]	51a[4]	42b	25c	53a
Percent fine sand	33a	31a	32a	31a
Percent very fine sand	2a	4a	11b	4a
Percent total sand	97a	93a	79b	96a
Percent silt	2a	5a	18b	3a
Organic matter (t/ha; 0-30 cm)	60.3a	98.7b	91.2b	34.6a
Total nitrogen (kg/ha; 0-10 cm)	278a	657b	622b	181a
Total nitrogen (kg/ha; 10-30 cm)	1010a	1082a	2080b	654a
pH A horizon	4.7	4.3	4.9	4.7

[2]Numbers represent site unit means.

[3]Plot weighted average determined for each particle size fraction; mass of individual soil horizons weighted by horizon thickness to a depth of 150 cm or bedrock.

[4]Data in the same row followed by the same letters do not differ significantly at the 5 percent level according to Scheffe's Pairwise Comparison Test.

to signal a critical difference between ecosystems dominated by conifers as opposed to hardwoods. Well-drained, coarse-textured soils (i.e., sands lacking a B2h horizon) are apparently so xeric that conifers can often outcompete hardwoods in the overstory. This is a good example of how the integrated ecological approach to forest site classification can lead to a deeper understanding of ecosystem function.

Site Unit 4.--The rolling ice contact hills and ridges of Site Unit 4 (fig. 1) are also dominated by *Acer saccharum*. The canopy is typically a dense and closed layer of *Acer saccharum* with scattered individuals of *Acer rubrum* and *Betula alleghaniensis* (table 2).

The more mesic conditions are reflected in the ground-flora by the occurrence of the *Gymnocarpium* group (table 3). Decreased coverage of the *Oryzopsis* and *Maianthemum* groups, along with the occurrence of the *Gymnocarpium* group, distinguishes Site Unit 4 from Site Unit 2.

Soils of Site Unit 4 contain more very fine sand and silt than those of Site Unit 2, which is ecologically closest to Site Unit 4. Site Unit 2 has an average of 9 percent very fine sand plus silt, compared to 29 percent for Site Unit 4 (table 2). Total nitrogen is greater by approximately 963 kg/ha (55 percent greater) in the upper 30 cm of Site Unit 4 soils. Site Unit 4 occurs on sloping topography in contrast to the level topography of Site Unit 2 (fig. 1).

Table 3--Occurrence of ecological species groups in dryland site units of McCormick Experimental Forest.[5]

• = 5-24% ● = 25-49% ⬤ = 50-100%

SITE UNITS in order of increasing moisture →

Ecological Species Group	Level Sand 1	Rocky South Slopes 9	Rocky Ridges 10	Steep South Sand 6	Thin Dry Soil 7	Flat Sand Gravel 2	Sloping Sandy Loam 4	Lower Slope Loam 5	Protected Valleys 11	Thin Moist Soils 8	Mottled Sand 3
Deschampsia	⬤										
Polygonum		●	⬤								
Cladonia	⬤	●	•	●	•						
Streptopus					•	⬤	⬤	●	⬤	•	●
Gymnocarpium							•	●	●		•
Viola								●			
Osmunda									●	•	•
Vaccinium	⬤	●	•	•	•					•	•
Pteridium	⬤	●	•	●	•	•				●	●
Oryzopsis		●	●	•	•	⬤	•	•	•	•	•
Polygonatum			●	•	•	●	●	●	●	•	•
Maianthemum	•	●	●	•	●	⬤	•		•	●	⬤
Dryopteris		•	●		•	⬤	⬤	⬤	⬤	•	●
Lonicera			•	•		●	•	•	●	●	●
Clintonia		•	•	•	•	•	•		•	⬤	⬤

[5]Dots represent the mean percentage maximum coverage of the group. Means less than 5 percent are not shown.

Site Unit 6.--The steep southerly slopes of Site Unite 6 are dominated by Pinus strobus. Stand structure is distinctly two-storied. Large Pinus strobus form the upper canopy. Below, Tsuga canadensis, Acer rubrum, and other species form the dense second story (table 2).

The sparse ground-flora coverage characteristic of Site Unit 6 consists primarily of species from the Cladonia, Vaccinium, Pteridium, and Maianthemum groups. The ecosystem can be distinguished from Site Units 2 and 4 by absence of the ecological species groups characteristic of the more mesic hardwood dominated ecosystems; e.g., the Streptopus and Dryopteris groups.

Soils of Site Unit 6 are nearly identical to those of Site Unit 1. Soil texture and degree of sorting are so close that similar depositional conditions could be hypothesized. Yet the landforms are markedly different. Site Unit 1 occurs on level outwash, whereas Unit 6 occurs on steep ice contact ridges. Organic matter and total nitrogen are somewhat lower than Unit 1. This is due to the thick A2 (albic) horizon characteristic of Unit 6.

The four deep-soil ecosystems at the dry end of a moisture gradient are ecologically similar. Yet, as the above contrast shows, each ecosystem can be easily distinguished using a combination of physiographic, soil, and vegetation characteristics. And even though the ecosystems are somewhat similar environmentally, they do differ significantly in certain edaphic factors. These differences are reflected in the occurrence and coverages of the various ecological species groups. Using the integrated ecological approach, the landscape can easily be stratified into ecosystems that differ in their composition, structure, physiographic and edaphic characteristics, and presumably also in their potential productivity.

THE USE OF GROUND-FLORA TO INDICATE EDAPHIC CONDITIONS

Foresters have long been interested in using vegetation to indirectly estimate soil conditions and potential productivity. We studied the distribution of selected ecological species groups over single and multifactor physiographic and soil gradients and found they could be effectively used to estimate edaphic conditions (Pregitzer and Barnes 1982).

In many instances, soil texture plays a key role in determining the amount of water available for tree uptake (Dosskey and Ballard 1980). Figure 2 depicts the distribution of three ecological species groups along a soil texture gradient for well-drained soils of the McCormick Experimental Forest. The presence of the Vaccinium group clearly identifies soils with more than 90 percent total sand (fig. 2). Presence of the Gymnocarpium group indicates soils of finer textures when compared to situations when the group was absent (fig. 2). By monitoring the qualitative and quantitative proportions of these three groups, it was possible to separate (map) the dryland sandy soils of the Experimental Forest according to texture.

Nitrogen is a key element and often limits potential productivity (Keeney 1980). Quantities of available nitrogen depend, among other things, on amounts of total nitrogen and pH. Within the Experimental Forest we found that the ecological species groups could be used to indicate significant differences in both total nitrogen and soil pH (Pregitzer and Barnes 1982). The Viola species group indicates significantly higher levels of total nitrogen (fig. 3) and significantly higher pH's (fig. 4). Presence of the group became a useful indicator of greater forest potential and was correlated with the highest mean canopy heights within the Experimental Forest (Pregitzer 1981).

The variation of ten physiographic-soil variables along two principal components is shown in figure 5. The first two component axes represent 57 percent of the total variation in the ten environmental factors used (Pregitzer and Barnes 1982). The figure shows that the distribution of

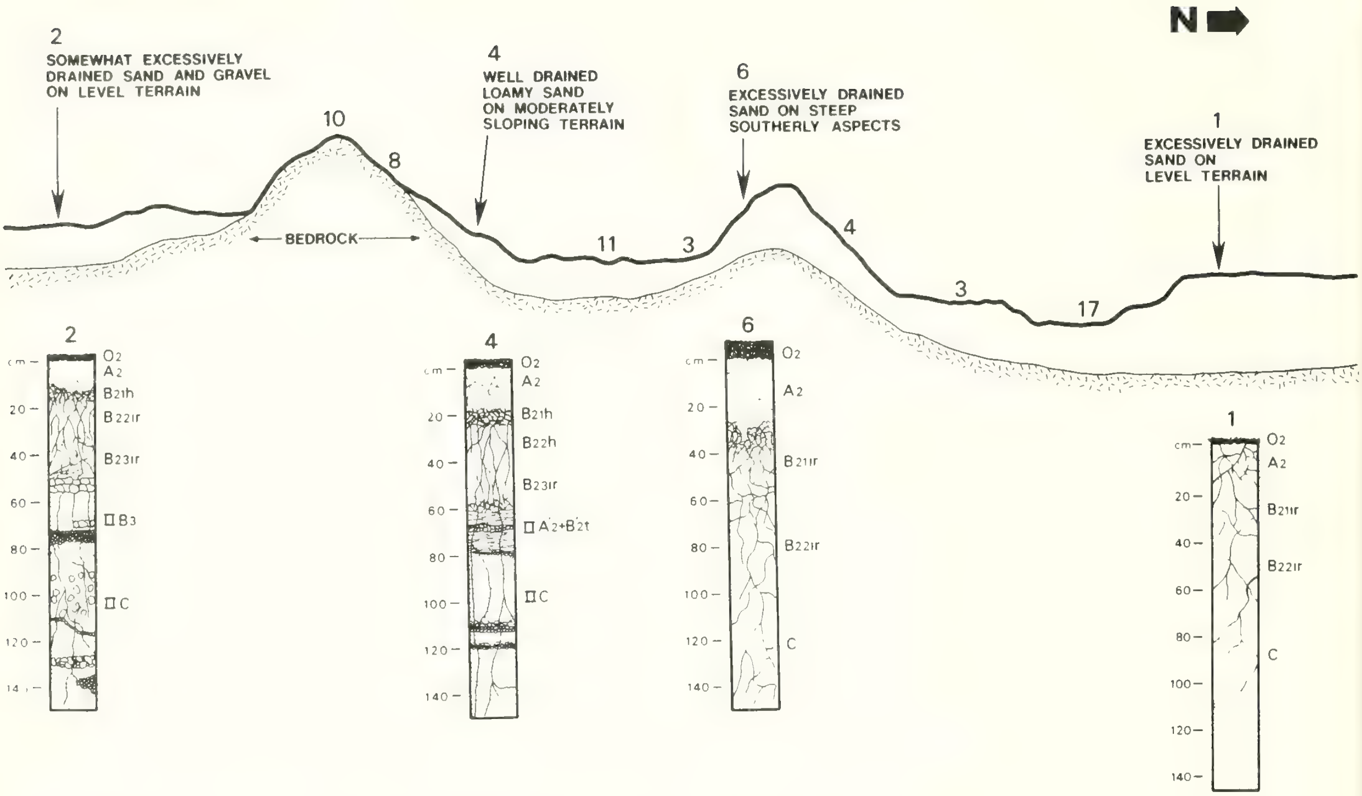

Figure 1--Typical topographic position and representative soil profile of the four driest site units occurring on deep soils relative to the topographic position of other site units. Site unit numbers correspond to those in table 1.

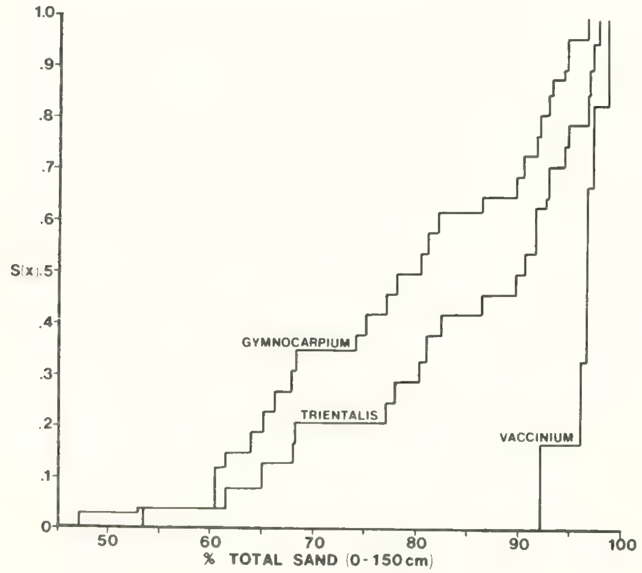

Figure 2.--Empirical distribution functions (Sx) of three ecological species groups along a soil-texture gradient. Only well-drained, deep soils are represented. The Gymnocarpium, Trientalis, and Vaccinium groups occurred 26, 24, and 6 times, respectively, in the 34 plots lacking soil mottling. (With permission from Canadian Journal of Forest Research. Copyright 1982 by the National Research Council of Canada).

four selected ecological species groups is mutually exclusive within the study area; i.e., each is confined to a different characteristic combination of physiography and soils. We found that the ecological species groups could be effectively used to indicate position along multivariate physiographic and edaphic gradients (Pregitzer and Barnes 1982).

FOREST SITE MAPPING

A map showing areas of equal forest potential accompanied by growth and yield functions and silvicultural recommendations for each site unit would be extremely useful to the forest manager. Using the integrated physiographic, soil, and vegetal characteristics of each site unit we were able to rapidly map the McCormick Experimental Forest (Barnes et al. 1982). One important feature of the multifactor ecological method is that the relationships among physiography, soils, and vegetation are understood. This enables us to key on such factors as topographic position, gross overstory composition, and stand density for aerial photointerpretation and rapid mapping of the various site units. Topographic position was a key factor in photointerpretation.

On the ground, the ecological species groups helped to indicate soil conditions. Their use enabled us to estimate soil condition and decreased the number of times we actually had to

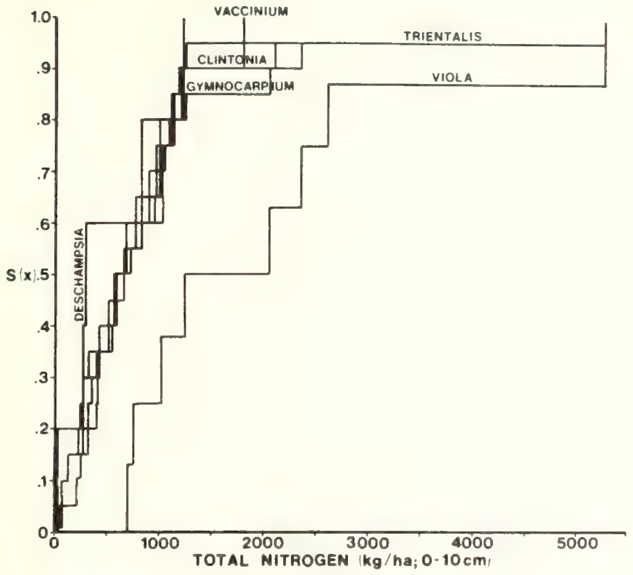

Figure 3.--Empirical distribution functions (Sx) of six ecological species groups along a soil total nitrogen gradient. The Deschampsia, Vaccinium, Clintonia, Gymnocarpium, Trientalis, and Viola groups occurred 5, 24, 37, 45, 53, and 8 times, respectively, in the 66 sample plots. (With permission from Canadian Journal of Forest Research. Copyright 1982 by the National Research Council of Canada).

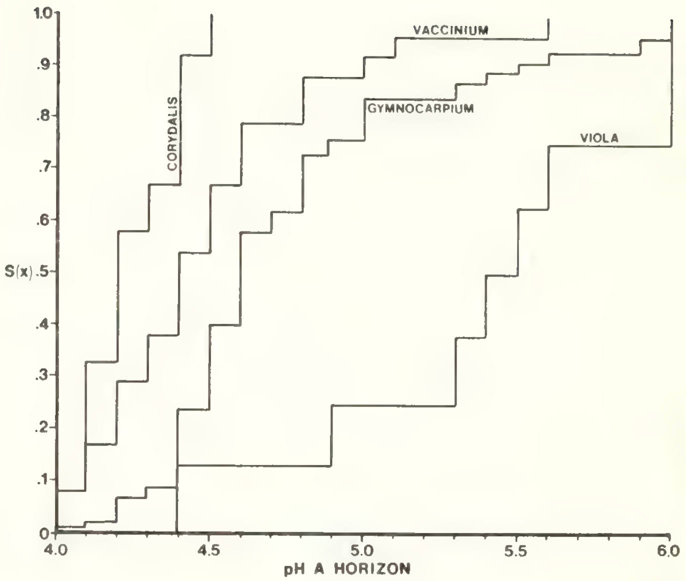

Figure 4.--Empirical distribution functions (Sx) of four ecological species groups along a soil pH gradient. The Corydalis, Vaccinium, Gymnocarpiu and Viola groups occurred 12, 24, 45, and 8 times, respectively, in the 66 sample plots. (With permission from Canadian Journal of Forest Research. Copyright 1982 by the National Research Council of Canada).

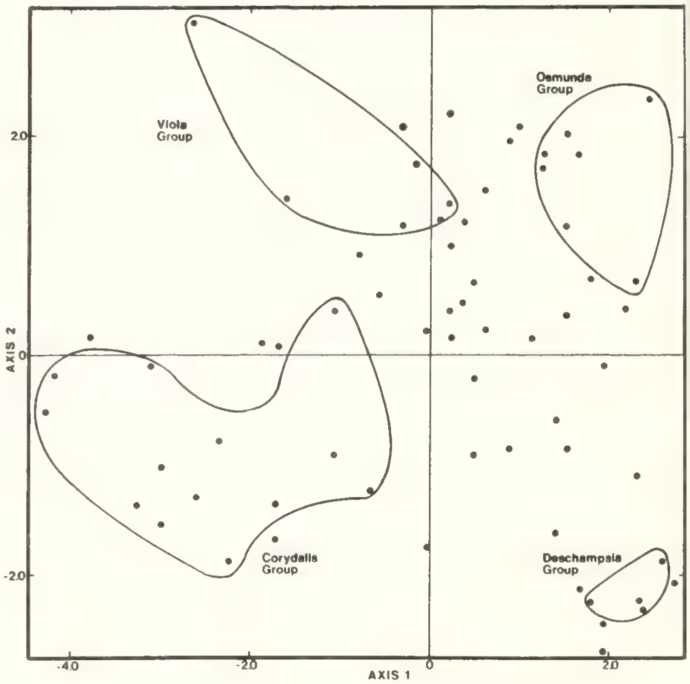

Figure 5.--Distribution of four ecological species groups over two physiographic-edaphic principal component axes. Contours represent regions of occurrence for each ecological species group. Dots represent the 66 plot locations along the 2 physiographic-edaphic axes. (With permission from Canadian Journal of Forest Research. Copyright 1982 by the National Research Council of Canada).

excavate soil while site mapping (Pregitzer and Barnes 1982; Pregitzer et al. 1983). The important point is that the integrated physiographic, edaphic, and vegetal approach made it relatively easy to classify and map the Experimental Forest and that mapping units were significantly different in many important physiographic and edaphic factors--factors that have often been shown to influence potential productivity (McClurkin 1963; Bowersox and Ward 1972; Carmean 1979; Green and Grigal 1979; Leak 1979; Munn and Vimmerstedt 1980). An integrated ecological approach to forest site classification and mapping has many advantages.

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SOME USES OF SOIL SURVEY INFORMATION FOR IMPROVED MANAGEMENT OF PLANTED FORESTS IN SOUTHEASTERN AUSTRALIA

Nigel D. Turvey and Henry Lieshout

ABSTRACT: In examining the role of soil survey information in forest resource management, we examine some constraints in obtaining soil survey information and the importance of understanding tolerances around soil map unit composition, purity and extent. Examples are given of the use of soil information in defining forest site, calculating tree responses to fertilizers, and in scheduling harvesting according to soil trafficability.

At A.P.M. Forests inclusion of soil information in an overall resource information system improved resource management. A computer-based information retrieval system is used for long-term yield management, short-term harvesting, and annual budgeting in cost activity centers.

Future system developments will provide resource maps defined by the user that will enable information to be taken back out to the forest for field management.

INTRODUCTION

Soil survey information is widely accepted in forestry and, like sliced bread, is in the class of "a good thing." Too often, however, soil surveys remain research tools and are only occasionally taken out of the backroom, dusted off, and paraded before a suitably impressed audience. In this paper, we examine some appropriate uses of forest soil surveys and look at some examples of the ways this valuable information base can be used with other resource information to improve the management and manipulation of the total forest and soil resource.

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GETTING SOIL INFORMATION

A soil survey for any purpose requires a good level of understanding between both the contracting organization and the soil surveyor because the complexity of soil in the landscape and the actual value of the resulting information are largely unknown before the survey is begun. This is embodied in a monetary risk both for the surveyor in his quotation to survey, and the organization in return on its investment in the survey. In addition, there is always the problem that an inadequate survey resulting from poorly defined map units will brand a soil survey as a failure. It is often difficult, however, to separate the results of an indequately defined survey from the reality of low soil variability and, therefore, low value of soil information; i.e., whether the soil survey was useless rather than inappropriate. It is important that, if a soil survey is appropriate, the soil information

be collected in such a way that it is useful.

It is necessary that the proposed uses of the survey be well defined and that minimum objectives be set to give information at the scale required. Stone's (1975) concept of a forest management spectrum is a useful one for examining soil survey information needs. For the "protected wild forest," soil information was needed to define plant associations and to allow repair of intensively used sites. Stone's spectrum increased in management intensity through "exploited" and "regulated" forests to the "domesticated forest" which required soil information for definition of forest production units, trafficability, erosion and hydrological control, species response to silviculture, pollution, and repair of special areas. This domesticated forest is a good description of planted exotic conifer forests in Australia.

The scale of mapping and intensity of survey are directly related to the information requirements of the forest managers and are of maximum intensity for the multifaceted operations of the manager of the domesticated forest. The detail of information retrieved from the landscape and spatially encoded in map units is a function of the scale of mapping. A soil map at a scale of 1:1,000,000 will reflect the strong influence of geology on soils. Landscape influences reveal catenary soil sequences and the effect of drainage as the scale increases toward 1:20,000.

Borough and Beckett (1971) showed (fig. 1) that costs of soil surveying increased dramatically for map scales 1:50,000 and became prohibitive for large areas at scales greater than 1:20,000. Figure 1 also shows the great cost of surveys based on or employing chemical characterization. If soil-dependent phenomena (e.g., tree growth, response to fertilizers, soil trafficability) can be linked to physical soil-profile criteria describable in the field (e.g., texture, structure, depth, color), then the cost of the survey can be kept down. Whether chemical characterization of a whole soil survey would greatly improve its interpretation is difficult to know. The fact that the vast majority of soil surveys are based on soil physical criteria begs the question of whether or not chemical information would have increased the value of the survey.

The objective in any soil survey at any scale is to minimize the within-class variance of the described map unit so that it becomes a useful unit for classification. Webster and Beckett (1968) showed that for an area under test the within-class variance for mechanical soil properties was low enough to allow for useful mapping, but that for chemical properties the variance remained too high for the map units to be useful. They pointed out, however, that this did not necessarily mean that the map based on chemical characteristics had failed, because if the chemical characteristics were of fundamental importance to the proposed land use, then it showed that the land itself was too variable for the purpose intended and that the land, rather than the map, was not suitable for the proposed enterprise.

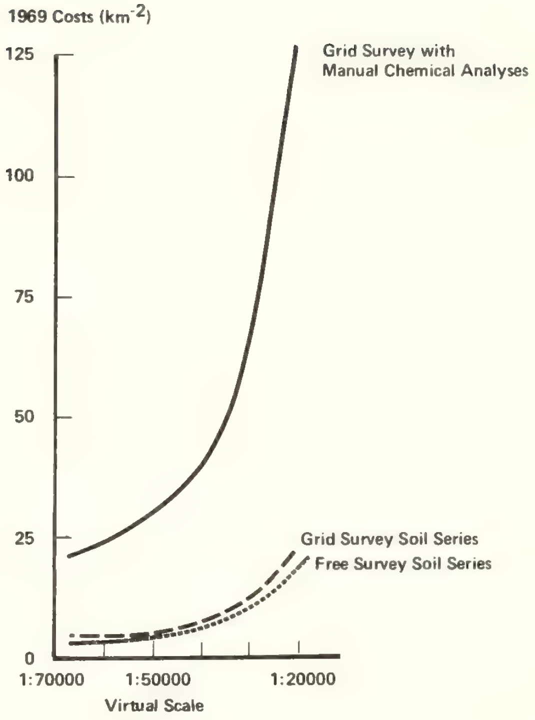

Figure 1.--The cost of soil survey in relation to virtual map scale (After Burrough and Beckett, 1971)

Reduction of within-class variance of soil characteristics will give different perceptions of the usefulness of the map units depending on the intended use of the map; e.g., response to fertilizers compared to roadability. It is best to map at the maximum detail level required and merge map units at a later stage if necessary; the reverse is not possible without recourse to further field mapping.

Often the first thing a forester will do when confronted with a soil map of his domain is to prove it "wrong" in his terms by going to a spot and showing that the soil there is different from that mapped. This is caused by a lack of understanding of tolerances for management purposes, between the soil profile at a given location and the soil association as a mapping unit. This is an important misconception of soil survey tolerances and needs to be explained carefully when introducing soil information into forest management. A misunderstanding of map unit composition, purity, occurrence, and extent can have important consequences in judgment errors when extrapolating forest yield from one growth plot or experiment on an individual soil profile to the geographical region or estate as a whole. The map cannot predict the profile class at a site more confidently than the definitions of its mapping units allow (Bie and Beckett 1971).

Table 1--The growth of Pinus radiata on fifteen map units identified on A.P.M. Forests' land in Gippsland, Victoria[3]

Map unit code	Dominant soil type in map unit	Principal profile form[1]	Great soil group[2]	MAI, age 10 years (m^3 ha^{-1} yr^{-1})
Gl	Glencoe sand	UC 2.33	Podzol	Gl 4.5 i
Gr	Gormandale sand	UC 2.36	Podzol	GR 5.3 l
Fl	Flynn sand	UC 2.21/Dy 4.21	Lateritic podzolic soil	Fl 7.8 h
Wl	Wellington sand	UC 4.21	Siliceous sand	Wl 7.9 gh
Mr	Morwell sand	UC 4.24/Dy 5.61	Siliceous sand	Mr 8.1 gh
Bl	Boolarra loam	Dy 3.62/Dg 2.61	Gleyed and yellow podzolic soil	Bl 8.2 gh
Ms	Maryvale sandy loam	Dy 3.41	Soloth	Ma 8.6 gf
Sd	Stockdale loamy sand	Dy 5.21/Dy 3.41	Soloth	Sd 9.1 e
MT20	Minor type 20	UC 5.11	Siliceous sand	MT20 9.4 ef
Mu	Munro map unit complex of Fl, Wl, Sd, Mr			Mu 10.5 d
Sc	Silver Creek loam	Gn 4.51/Dy 2.11	Brown podzolic soil	Sc 11.9 c
Je	Jeeralang loam	Um 4.11	Litosol (where shallow)	Je 14.1 b
Na	Narracan clay loam	Gn 4.31	Brown podzolic soil	Na 14.2 b
Th	Thorpdale clay	Gn 4.11	Krasnozem	Th 14.9 ab
Ba	Balook clay loam	Gn 4.31/Gn 4.81	Brown podzolic soil	Ba 16.0

Scale: 2 4 6 8 10 12 14 16

Common letters not significantly differen 5 percent level (Duncan's Multiple Range)

1/ Northcote (1979)
2/ Stace et al. (1972)
3/ Table from Turvey (1980)

SOME SPECIFIC USES OF FOREST SOIL INFORMATION

Some of the examples given here are taken from our experience with a soil survey for planted Pinus radiata D. Don forests in Gippsland, Victoria, in southeastern Australia, established by Australian Paper Manufacturers Forests Pty. Ltd. Some details have been described in Turvey and Poutsma (1980) and Turvey (1980). The area has a diverse geological history ranging from Silurian mudstones and Tertiary basalts to Holocene sand ridges, clay soils, and recent floodplain deposits. Rainfall over the region ranges from 1 400 mm yr^{-1} on the mountain ridges to 600 mm yr^{-1} on the coastal plains.

Forest Yield Prediction

Delineation of forest site for the prediction of tree growth is one of the most common uses of forest soil information.

Site is a useful concept in plantation forestry if it defines different areas of productivity. The factors which have the greatest bearing on productivity in the particular region are used as the delineators of site. Consequently, variables used to define site in one region may not be of importance in other regions. Delineators of site are more easily defined for naturally regenerated indigenous forest species than for the planted exotic species of the domesticated forest. In the domesticated forest, one introduced species will be established on a wider range of sites than was covered previously by any one indigenous tree species.

In many areas the domesticated forest will be established on soils that have had a variable land use history and may have gone out of agricultural production due to economic circumstances. Such soils may have been cultivated and fertilized for some years or may well be eroded and of reduced fertility. For the domesticated forest the old concepts and definitions of forest soils and site may need to be modified and added to because a wide range of soils may become forest soils by default.

If we look again at the purity of soil map units and the need to reduce the soil variance within the map unit, we can extend this concept to examine the map unit as a basis for the classification of site. Here the same concept applies in that the map unit is a clear definition of site if the variance of the measured site parameters such as height, basal area, or volume are minimized by grouping into classes (map units). This was done for Pinus radiata at age 10 years in Gippsland (Turvey 1980). Some 3,500 inventory

plot tree measurement records were assigned to soil map units and an analysis of variance performed on tree volume data to test for differences between soil map units. The results in table 1 show that individual map units by themselves do not form strong site indicators, but statistical groupings cover map units with soils of similar profile types to form site classes, and these site classes overlap. The data in table 1 are for stands at age 10, and the sensitivity of site classification and the value of single map units can be expected to improve as trees occupy the site and the full complement of site factors impinge on tree growth.

The formation of P. radiata yield curves by soil types in figure 2 was based on growth plot data (Turvey 1983). Non-linear regression based on the Mitscherlich growth model was used to fit curves through the growth plot data. The age 10 analysis in table 1 was done with map units as classes and the growth plot data were analyzed according to the soil profile under each growth plot. Each of the soil types dominates a map unit and gives its name to the map units, which also include 10 to 40 percent of other soil types. The greater spatial sampling frequency of the inventory plots test the homogeneity of the map units as site classes, whereas the growth plots demonstrate the full effects of the dominant soil type in each map unit as a delimiter of site. Reconciling the two approaches required some conceptual flexibility; and it is clear that extrapolation of yield from the growth plot yield curves to the whole extent of the map unit requires error terms associated with both the regression equation and goodness of fit and the confidence limits around the spatial and internal variability of the map unit as a classification.

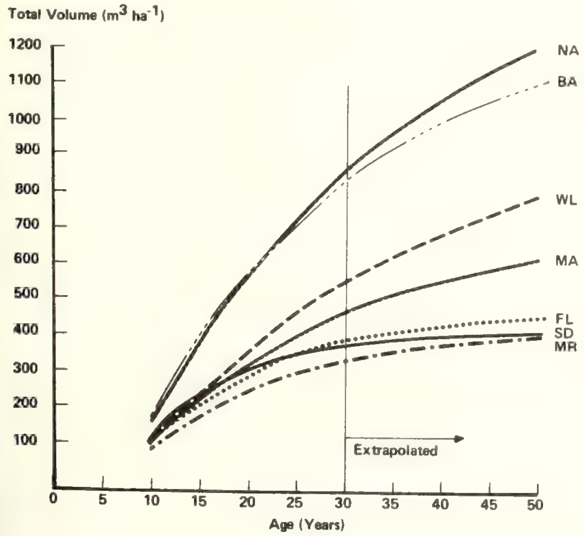

Figure 2.-- Total Volume Accumulation for Pinus Radiata on soil types in Victoria, Australia

Basing forest yield predictions on soil map units can result in either a dramatic increase, a dramatic decrease, or no change in estimated yield of the mapped estate depending on the framework and quality of previous yield estimates; in the forest manager's view, the value of the soil survey can rise or fall accordingly.

Prediction of Forest Response to Fertilizers

Once soil-type and wood-yield relationships are established, the question arises as to how much more wood volume can be obtained by fertilizer application. In this case it is both expensive and time consuming to test the variance of response in tree growth to fertilizers by map units because controlled fertilizer additions would have to be made on a very large number of sample points within each map unit to ensure a true measure of the variance of the map unit response. Here the intuition and skill of the researcher is required to classify soils into groupings so that the relatively limited fertilizer testing program that is feasible will result in useful data on fertilizer response. Such data are collected from experiments on soil types and need to be interpreted for application to map units and subsequently the mapped forest estate.

Kushla and Fisher (1980) have shown how the use of groupings of soils, classified according to drainage and depth to and nature of the B horizon, can be used to predict Pinus elliottii response to nitrogen and phosphorus fertilization. They found that responses to fertilization, when grouped by soil groups, provided average responses within the soil groups that were useful for making operational decisions about fertilizer application. Stepwise regression to "explain" volume response to fertilizers improved the prediction of volume response within soil groups but produced an assortment of physical and chemical parameters for each soil group. Nevertheless, this analysis showed the robust nature of the soil groups which are readily recognizable by soil profile characteristics in the field.

The analysis by Kushla and Fisher (1980) covered both an extensive geographical area of the lower coastal plain of the southeastern United States and a wide range of soils from excessively drained sands to poorly drained, fine-textured soils. Much of the success of such a classification of fertilizer response must be attributable to the spatial and textural ranges of variability of the sampled soil population.

In the Pacific Northwest of the United States, regional fertilizer tests in Douglas-fir and western hemlock (Anon 1980) have shown very useful fertilizer response trends that are consistent and definable by fertilizer rate and stand age class. The apparent lack of response by site may in this case be attributed to low real variability of soils in comparison to the southeastern United States example, or an insen-

sitivity of measured tree parameters such as site index to discriminate between soil types. Shumway and Atkinson (1978) demonstrated that anaerobically mineralized soil nitrogen was negatively correlated with growth response to applied nitrogen and that this was a discriminatory site variable. In this instance, however, the overall apparent lack of variability in regional response greatly simplified operational use of fertilizer prescriptions.

The two examples above were based on trials established approximately concurrently on a selected regional basis, and as such are reasonably well controlled experimentally. Another approach is to use data from old fertilizer trials and try to form some sensible response trends from a mix of trials of different ages and durations on a mix of soil types and with a range of fertilizer rates, mixes and types. Such an exercise in data salvage was done for P. radiata in Gippsland (Turvey unpublished data). The objective of the exercise was to create regression models within soil groups to predict height, diameter and volume response of P. radiata to applications of N, P, and K fertilizers with or without weed control. This Fertilizer Response Trend Surface (FERETS) could then be used to predict volume growth up to age 10 for various treatments applied at establishment. A similar use of regression models from a large number of trials was made by Rosvall (1979) in Sweden. There, two equations were used to predict fertilizer response over a range of stand and site conditions, with the objective of improving estimates of response to fertilization.

In the Gippsland example, soils were placed into five groups on an assumed criteria based largely on similarities in observed profile criteria, and also on the purely mechanical criterion of ensuring sufficient data representation within classes. Some 278 fertilizer and weed control treatment means were extracted from trials established between 1958 and 1977. The responses within soil groups calculated from regression equations were tied to known yield within the estate's inventory data base. In figure 3 the O (old) regime represents the inventory data at age 10 which was used to create the site classes in table 1 and the M (medium) and I (intensive) regimes represent responses to increased levels of fertilization and/or weed control.

The calculated responses to different levels of silviculture at establishment have proved extremely useful in costing the value of fertilizer and herbicide additions, and indeed some such basis is essential for silvicultural cost analysis. As a general principle, a minimum amount of additional effort spent on raising productivity on a fertile site will result in more wood grown than if a great deal of effort is spent on raising productivity on far less fertile sites. The exceptions will be in meeting specific deficiencies at moderate costs and thereby facilitating site occupancy. The overall trend of fertilizer use in this region is to promote tree growth to a level that is inhibited further

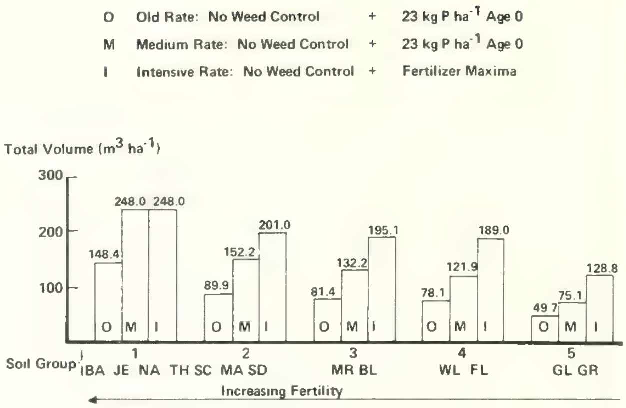

Figure 3.--Predicted Total Volume at age 10 for different rates of silviculture for Pinus radiata, Victoria, Australia

by limits of rainfall and soil water storage. Once the soil nutrient status constraints to growth have been lifted, soil hydrological characteristics and rainfall play a greater role in setting the upper limits to tree growth.

The results in figure 3 combined with information on areal extent should put nutrition research problems in a true perspective. This should be true of all soil surveys, even on a world scale; Young (1979) pointed out in the worldwide soil survey done by FAO that with the emphasis of published work on tropical soils on laterite "who would have thought that it would prove to be considered worthy of mapping over less than 5 percent of Africa". The same inference can be placed on the vast number of nutritional and physiological studies done in sand, relative to the proportion of forests on sandy soils.

Trafficability

Many soil scientists trained in agricultural soils tend to consider soils primarily as media for plant growth. There is nothing more distressing to a forest organization, however, than to find that market commitments cannot be met because machinery cannot be moved into a scheduled harvest area due to wet conditions, or for a harvesting planner to see a quarter of a million dollars on wheels sink slowly into the unmapped mire. Thus, trafficability ratings have been a strong impetus for forest surveys by organizations such as Crown Zellerbach (De Bell et al. 1975) and Weyerhaeuser (Steinbrenner 1975).

In our own case in Gippsland, trafficability ratings (Turvey 1980) were based on predicted hydrological characteristics of the soils taking into account vertical changes in both texture and structure in the soil profile. These groupings were reinforced by experience with logging machinery over an extremely wet winter. A remarkable improvement in scheduling areas to be

harvested was achieved through the introduction of just three classifications of soils trafficable in a wet winter, a normal winter, and summer only.

Scheduling "wet winter" trafficable soils for harvesting at the peak seasonal limits to trafficability has ensured continuity of harvesting operations through winter. This has the advantage that soil damage through trafficking, known to be severe in structureless soils when wet, can also be minimized.

SOIL AS A COMPONENT IN RESOURCE MANAGEMENT

The managers of any forest organization have large repositories of information. This information is often disparate in nature and stored by different people for different purposes. Efficient management of the total resource involves efficient management of the information on which to make decisions about the resource. Computerized information retrieval systems are a means to improve management, and the utility of soil and other information can be improved greatly by computer software that allows manipulation of map units for different interpretations (Jansen and Fenton 1978).

Soil information is just one source of information in what can be a vast array ranging through records of: environmental factors (rainfall, slope, aspect, site history); stand statistics (species, age, stocking, growth rate, genotype, fertilizer, weed control); crop type (log size, utilization, pulp log, sawlog, peeler log, wood quality); economic costs (treatment cost, maintenance cost, wood growing cost, harvesting cost, taxation); and legal records (ownership history, resumptions, easements, ratable value, local government area). Because forestry is a land-based enterprise, it is not unreasonable to tie many records back to the land base and soil map unit. The following three cases are examples of the way soil information has been incorporated into our forest management system in Gippsland.

Long-term Plantation Yield Management

The Gippsland estate of 80 000 ha has been segregated into some 200 planning coupes, each classified into 1 of 14 soil map units with attendant fertilizer and weed control prescriptions. A stand model to generate optimum alternative management strategies for a long-range planning model (Turner et al. 1977) allows the user to evaluate different intensities of silviculture and subsequent wood yield over a wide range of soil types in the P. radiata plantations.

Forest managers are vitally interested in such questions as what establishment techniques should be applied to which sites, which stands should be fertilized, what dose of chemical weed control should be applied, how frequently this should occur, and what the economic implications are for these different regimes. Some 6,000 possible strategies are produced and reflect influences of plantation growth, cutting schedule, silvicultural costs, etc. An optimized strategy for a selected coupe is then computed.

Short-term Cutting Model

Detailed annual cutting plans for P. radiata plantation in Gippsland are prepared with the aid of a computer system (Dargavel and Marshall 1976). Measured tree data from the data base are extracted and manipulated so that stands may be selected for cutting by preset decision rules, using a true/false decision table to make the computation efficient. The addition of map unit trafficability classifications is particularly useful in operational use and planning. Areas are ranked according to their readiness for thinning, but only when seasonal trafficability constraints are met. This cutting model uses seasonal and product constraints to control wood flow from the planted forests.

Budgeting - Cost Activity Centers

Silvicultural activity centers related to land parcels are created and divided into plantation areas considered homogeneous for treatment purposes in the early years of establishment. Because many of the silvicultural operations are prescribed according to soil type and because soil type also strongly influences the performance of machinery and hence job cost, cost activity centers are based on soil map units and forest compartment location.

A Forest Operations Control System (FOCS) aids the area manager so that resources required and costs in using such resources can be allocated to "cost activity centers" and accumulated as desired to present a budget within company resource and financial constraints for the ensuing financial year. During the financial year, incurred resource usages--labor, materials, etc.--are compared with the budget so that job performance can be closely monitored. The detail reported provides the manager with a fast and complete analysis of the operations.

Prior to the beginning of a new financial year, cost activity centers are formed to create identities suited to the purpose of budgeting, comparison, and operational prescriptions for day-to-day management of the plantations.

DATA BASE MANAGEMENT

The existence of accessible, amendable, complete, and accurate land use records stimulates and aids better resource management. The increasing complexity of resource analysis and land use planning, however, has prompted technological advances in comprehensive geographical referencing systems, permitting rapid retrieval, manipulating, analysis and displaying of geographically based data.

The efficiency of data storage, retrieval and update are dependent largely upon the storage

medium and the file structure within the information system. File structure varies widely depending on the complexity of the data, how those data are to be used, and how frequently. The essential processing elements of a geographical information system are multiple access in terms of data encoding and input processing, data management, data manipulation and analysis, retrieval, and display. With efficient data storage and handling systems, highly capitalized and intensively managed plantations can be brought further to realize their full productive and economic potential.

Our future aim is the implementation of a resource display system to assist in decision making by the field manager. The forester covers such a range of functions and has such a range of personalities and training that he/she should be supplied with a map to suit the purpose in hand. This map can be written on, filed, given away, or thrown away. A new one is printed on the terminal by request. Soil information by itself is only one piece of information that needs to be brought together with from one to five other bits of information out of a list of twenty or so; e.g., slope, aspect, rainfall, planting year, thinning history, fertilization, weed control, gravel deposits, etc. If these pieces of information are stored on separate computer files they can be merged by user commands to produce a custom map, thereby taking soil management information back out to the on-site soil base. Informed foresters will know the sort of soil they are working with in their domain, and a soil map will tell them little that is new, but a flexible information retrieval system puts all the experience of the forest organization together to enable them to better manage their soil-based forest activities.

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BIOMASS PRODUCTION IN *PINUS CARIBAEA* L. of DIFFERENT AGES IN THE SAVANNA ZONE OF NIGERIA

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ABSTRACT: Five stands aged 4, 6, 8, 10 and 13 years were studied to characterize production of dry matter by *Pinus caribaea* L. at Afaka in the savanna zone of Nigeria. Using an allometric regression model, estimates of dry matter production were 13.951, 43.372, 66.583, 96.062 and 120.729 x 10^3 kg/ha for 4, 6, 8, 10 and 13-year-old plantations, respectively. In all the age series, the dry matter of bole material consistently represented the greatest proportion of the standing biomass which amounted to 55 percent followed by roots (19.5 percent), needles (12 percent), and branches (9.7 percent). During early plantation-establishment phase (0-4 years), the buildup of standing biomass was slow. The period of maximum dry matter accumulation was between 4 to 10 years when the mean rate of dry matter accumulation amounted to 13.685 x 10^3 kg/ha excluding litter fall and losses due to pruning operations.

When compared to biomass measurements of *P. caribaea* of similar ages at Ibadan, Nigeria, the estimates of the present study were found to be lower by almost 50 percent. This contrast was attributed to differences in stocking density, mortality rate, and length of the growing season.

INTRODUCTION

Pinus caribaea L., an introduced conifer, is being planted in reforestation programs for pulp wood production in different localities in Nigeria. In the savanna region of Nigeria, *P. caribaea* has potential for good growth on the high-altitude sites and in the more moist parts where annual rainfall exceeds 1 050 mm.

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There has been a growing interest in the studies of biomass and dry matter production following the recognition of the forest ecosystems as a renewable natural resource. Such studies can increase our understanding of the growth of forest stands as well as the ecological impact of continuous forest production. Woodland ecosystems of the world differ greatly in their biomass and organic productivity. Madgwick (1976) reviewed estimates of the biomass of individual stands on a worldwide basis with most of the studies confined to the temperate and subtropical regions of the world. The work of Rees and Tinker (1963) on an oil palm plantation was a

pioneer study on managed plantations in the tropics. More recently, Egunjobi (1975, 1976) and Egunjobi and Bada (1979) provided estimates of dry matter production of *Pinus caribaea* at Ibadan in the high forest zone of Nigeria. The objective of the work reported here was to study biomass production of an age series of *P. caribaea* plantations in the savanna zone of Nigeria.

METHODS

Study Site.

The experimental area is situated within Afaka Forest Reserve, Kaduna State, Nigeria. The original vegetation before plantation establishment was classified as the Northern Guinea Savanna (Keay 1959). It is located at latitude 10°37'N. and longitude 7°15'E. at about 610-m elevation. The relief is flat with a slope of less than 1 percent. The mean annual rainfall is about 1 250 mm but yearly totals show wide variation. The five months from November to March are virtually without rain. The mean annual temperature is 25°C. The soils of the reserve were derived from igneous (granite) and metamorphic (gneiss and quartzites) basement complex rocks and sandy drift material transported by water or wind. The soils were classified as ferruginous tropical soils (Barerra and Amujo 1971) and have dominantly kaolinitic type of clays and show iron accumulation in some parts of the profile. The A and B horizons at Afaka are usually sandy loam or loam in texture.

The Stands.

The *Pinus caribaea* stands were planted within 2 km of each other at Afaka in 1968, 1971, 1973, 1975, and 1977. The variety is *hondurensis* originating from Mountain Pine Ridge in Belize. Different espacements were adopted thus giving rise to differences in stocking density (table 1). The five plantations had been pruned to 2.40 m at different periods.

Field Procedure.

In each of the five stands (4-to 13-years-old) a sample plot of approximately 0.050 ha was selected and all trees within the plot were measured for height and diameter at breast height (1.30 m). The trees of each plot were then grouped into three diameter classes (shown in table 2). Three trees of average diameter were harvested for each diameter class making a total of nine trees for each stand. This procedure was carried out in July 1981.

Stems were divided into 1-m sections and total fresh weight was determined prior to sampling for moisture content. Total fresh weights of the needles and branches were similarly determined. All roots of 10 (2 for each stand) out of the 45 felled trees were thoroughly excavated and weighed to estimate root biomass as suggested by Egunjobi and Bada (1979). Subsamples of the tree components were taken to the laboratory and dried to constant weight at 80°C for moisture content determination.

Estimation of Stand Biomass.

The standing crop biomass was estimated from allometric regression:

$$\mathrm{Log}_e Y = a + b \,\mathrm{Log}\, e^{d}$$

where Y is dry weight of tree component, d is the diameter at breast height, a and b are regression constants. Total dry weight of stand components were found by applying these regressions to unsampled trees. This method gives reasonably close estimates of dry weight of *P. caribaea* stands in Nigeria (Egunjobi and Bada 1979).

RESULTS AND DISCUSSION

Stand Characteristics.

Summary of measurements on stand characteristics are shown in table 1. The plantations are all located on fairly uniform soil (Afaka sandy loam). The stands were planted at different spacings:

Table 1 - Characteristics of *Pinus caribaea* stands of different ages planted at Afaka, Nigeria

Year of Planting	1977	1975	1973	1971	1968
Age (years)	4	6	8	10	13
Stocking (trees/ha)	792	933	999	1,199	1,201
Dead or Missing (trees/ha)	222	81	333	133	481
Mean dbh $\pm$ SE[1/] (cm)	8.9 $\pm$ 0.2	13.0 $\pm$ 0.3	15.3 $\pm$ 0.3	16.9 $\pm$ 0.3	17.2 $\pm$ 0.3
Basal Area (m^2/ha)	5.60	12.72	19.98	26.52	27.67

[1/] SE = Standard Error of the Mean

Table 2 - Standing biomass (kg/tree) of tree component parts in the different diameter classes of 5 different aged plantations of Pinus caribaea L.

Age (yrs)	Diameter class (cm)	Component parts				
		Bole	Branches	Needles	Root	Total
4	6 - 9	6.16	1.14	1.48	2.23	11.10
	9 - 12	11.68	2.20	2.80	4.31	20.99
	12 - 15	23.80	4.53	5.67	8.96	42.96
Mean		13.88	3.32	4.92	5.17	25.02
6	8 - 11	11.16	2.09	2.80	4.09	20.14
	11 - 14	21.79	4.12	5.18	8.15	39.24
	14 - 17	34.55	6.60	8.18	13.09	62.42
Mean		22.50	4.27	5.39	8.44	40.60
8	12 - 15	25.67	4.87	6.09	9.64	46.27
	15 - 18	39.00	7.46	9.22	14.83	70.51
	18 - 21	56.38	10.24	13.29	21.67	101.58
Mean		40.35	7.52	9.53	15.38	72.78
10	12 - 15	26.12	4.96	6.20	9.82	47.10
	15 - 18	43.15	8.27	10.19	16.46	78.07
	18 - 21	60.01	11.57	14.14	23.11	108.83
Mean		43.09	8.27	10.18	16.46	78.00
13	15 - 18	41.94	8.03	9.91	15.98	75.86
	18 - 21	60.76	11.71	14.31	23.40	110.18
	21 - 24	84.64	16.41	19.88	32.19	153.84
Mean		62.45	12.05	14.70	24.10	113.30

3.14 m x 3.14 m for the 4- and 6-year-old stand, 2.74 m x 2.74 m for 8- and 10-year-old stand, and 2.44 m x 2.44 m for the 13-year-old stand.

The wider spacings were intended to allow tractor cultivation and weeding of the stands in two directions. The differences in spacing and the fact that the stands suffered mortality at different rates have resulted in different tree stocking densities. Both tree diameter at breast height and basal area increased with plantation age.

Dry Matter Contents of Different Tree Components.

Despite uniformity of site conditions and cultural treatment, tree dimensions and biomass varied considerably at each stand (table 2). The variability was more pronounced in the younger than in the older stands. For example the ratio of the largest to smallest tree biomass (kg/tree) recorded in the 4-year-old stand was 3.9, but the corresponding ratios for the 10- and 13-year-old stands were 2.3 and 2.0, respectively. This gives an indication of decreasing variability with plantation age. Such variations are common and have been observed in studies of monoculture plantations (Egunjobi 1975 and Forrest and Ovington 1970).

The average biomass for the different tree components (bole, branches, needles, and roots) increased with diameter class and stand age with all attaining their peak values in the 13-year-old plantation.

Standing Biomass.

The standing biomass per hectare for each diameter class was calculated using the allometric model:

$Y = n.ad^b$

where n is the number of trees per hectare in the diameter class and d is the mean diameter of n trees.

The total dry weight for each age group was estimated from the sum of biomass of the three diameter classes in the stand. Results are presented in table 3. The allometric model was found to be most acceptable as it showed the best regression fit among the models that were tried. The R^2 values range between 0.75 to 0.97. The correction factor, $e^{0.5}\ s^2$ where s^2 is the variance of the regression line, suggested by Mountford and Brune (1973) was applied to correct any bias due logarithmic transformation. The

Table 3 - Standing biomass (10^3 kg/ha) in plantation of Pinus caribaea L. of different ages

	Age of Stand in Years				
	4	6	8	10	13
Bole	7.734	24.312	38.013	52.655	65.360
Branches	1.451	4.237	6.689	8.710	10.338
Needles	1.856	5.294	7.820	10.963	14.113
Root	2.845	8.383	12.289	19.331	24.625
Total aboveground	11.041	33.843	52.522	72.328	89.811
Total (by summation)	13.887	42.226	64.811	91.659	114.436
Total (weight regression)	13.951	43.372	66.583	96.062	120.729

corrected estimates did not differ appreciably from the uncorrected. The correction was

Table 4 - Mean annual biomass production (10^3 kg/ha) of aboveground material of Pinus caribaea of different ages

Period (years)	0 - 4	0 - 6	0 - 8	0 - 10	0 - 13
Bole	1.93	4.05	4.75	6.58	5.02
Branches	0.36	0.70	0.83	0.87	0.79
Needles	0.46	0.88	0.98	1.10	1.08
Total	2.76	5.64	6.56	7.23	6.91

therefore discounted in view of the degree of accuracy acceptable in this type of study.

As the plantations age, the dry matter production builds up progressively and by 13 years amounts to 120.729 x 10^3 kg/ha excluding ground litter and losses due to pruning operations. In all of the age series the amount of bole material represents the greatest proportion of the total biomass (about 54-57 percent) followed in order of decreasing magnitude by roots (about 20 percent), needles (12 percent) and branches (about 10 percent). These proportions are similar to those quoted by Egunjobi (1975) for P. caribaea.

Mean Annual Biomass Production.

During the early plantation establishment period (0-4 years) the buildup of standing biomass was slow but thereafter the rate of dry matter accumulation increased. This trend is illustrated by the data in table 4. The mean annual dry matter production varies considerably with plantation age but the pattern of variation is similar among the different tree components.

The period of optimum dry matter accumulation by the aboveground material is between 4 to 10 years. The net increase in standing crop between 4- and 10-year-old stands amounts to 82.111 x 10^3 kg/ha giving a mean rate of dry matter accumulation of 13.685 x 10^3 kg/ha. The mean annual litter fall in the 10-year-old stand was 3.683 x 10^3 (Kadeba and Aduaji, unpublished data). Taking litter fall into account, the mean rate of dry matter accumulation becomes 17.368 x 10^3 kg/ha. This is about 50 percent of the estimate obtained by Egunjobi and Bada (1979) for P. caribaea at Ibadan, Nigeria.

Comparison with Other Studies.

Measurements of stand productivity for Pinus caribaea, P. patula, and P. radiata D. Don from both tropical and temperature regions are presented in table 5 for comparison with the present study. Compared with the data of Madgwick et al. (1977) the 10-year-old stand at Afaka had about the same dry weight as 10-year-old P. radiata in New Zealand. In relation to the estimates obtained for a 10-year-old stand of P. patula in Tanzania (Lundgren 1978) and 5-year-old stand of P. caribaea in Brazil (Chijioke 1980), the dry matter production in this study was smaller by far when compared to the biomass production obtained in these studies.

Comparison of the productivity of the Afaka stands with similar productivity study of P. caribaea in Nigeria depicted the same trend as above. For example the aboveground standing biomass in a 10-year-old stand in the present study was estimated at 72.328 x 10^3 kg/ha. But Egunjobi and Bada (1979) obtained a value of 144.427 x 10^3 kg/ha for a 10-year-old stand of P. caribaea at Ibadan in the high forest zone. At 5, 6, and 8 years, the biomass production at Ibadan was also distinctly superior to biomass production of the same age at Afaka in the Northern Guinea Savanna. Many factors seem to have accounted for this observation. Apart from the lower stocking rates and higher tree mortality at Afaka, the length of the growing season is apparently longer at Ibadan. Afaka is,

Table 5 - Aboveground dry matter (10^3 kg/ha)

Species	Age (yrs)	Location	Number of trees/ha	Dry weight	Source of data
Pinus caribaea	10	Afaka (Nigeria)	1199	72.328	Present study
P. caribaea	10	Ibadan (Nigeria)	2866	144.427	Egunjobi and Bada 1979
P. patula	10	Shume (Tanzania)	1400	249.00	Lundgren (1978)
P. caribaea	5	Sao Miguel (Brazil)	981	66.000	Chijioke (1980)
P. radiata	10	Kaingaroa (N. Zealand)	544	71.600	Madgwick et al. (1977)

moreover, located in the hot subhumid (900-1 300 isohyets) tropics. For satisfactory growth of Pinus spp., Afaka represents the upper limit of latitudinal position beyond which both soil and atmospheric moisture regimes become limiting factors to establishment and growth of Pinus caribaea.

Despite rather marginal biomass production there is still great incentive for plantation forestry of Pinus caribaea as a viable alternative source of wood fiber and industrial timber. This is more so in the tropical savanna where the harvestable potential of the woody biomass has fast diminished (Evans 1976) and in some places is nonexistent following decades of grazing, cultivation, bush burning, and overexploitation.

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MODELING APPROACHES TO FOREST PRODUCTIVITY

Gordon E. Warrington

ABSTRACT: Models developed for predicting resource outputs from forest lands should reflect both land management and ecological processes. Natural resource management relies on forecasts and interpretations to guide the use of various practices in the manipulation of the forest environment. Forest managers need information about the potential quantity of resource outputs, job quality, location of practices, timing of practices, and mix of outputs in order to evaluate management alternatives. A conceptual framework reflecting the way management and ecological processes interact to produce outputs provides a basis for bringing together individual models characterizing these processes. Optimization and process models are being used by the Forest Service, U.S. Department of Agriculture, in the development of alternative ways of managing forest productivity. These models, when used together, become flexible analytical tools for exploring complex relationships in the process of developing information for use in forest management.

INTRODUCTION

Today's forest manager depends on forecasts and interpretations that can be produced from environmental data to guide land management practices. In meeting this need, models are used to help turn technical data into management information by organizing complex ideas, forms, and processes into a representation of reality. These models are programed decisions that apply to routine or recurring situations which can be resolved through predetermined rules and procedures. Development of appropriate models for processing environmental data into information about natural resource outputs and conditions requires an understanding of both management and environmental processes. Each part of the management-, planning-, and decision-making process has specific characteristics and requirements that should be used to guide the selection of appropriate modeling approaches.

Two modeling approaches being used by the United States Forest Service are, optimization models for evaluating ways to allocate resource outputs, and process models based on relevant environmental relationships to predict resource outputs. When developing management direction, both types of models become analytical tools that are used to create information about the ways environmental processes can be expected to respond to management practices. These modeling approaches are discussed within a management framework so that the contributions of individual parts of each process can be related to managing forest productivity.

MANAGEMENT PROCESSES

A forest manager must address the problem of providing various products within the productive capabilities of the resources. In most cases products such as saw timber, pay the bills and receive the most attention. Forests also supply livestock forage, recreation, wildlife habitat, and water. In addition, a number of managerial and environmental needs which must be met in order to maintain the long-term production of beneficial forest resources. For example, when preparing for a timber harvest a volume of timber is targeted, a location is selected, conservation practices are chosen for soil and water protection, plans are made to dispose of logging residues at a

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minimum economic and environmental cost, and the harvest is scheduled to fit in with weather conditions and maintain a supply of logs for the mill. The forest manager is looking for a combination of practices that will lead to a future state of forest production that is at least as good as all other possible states.

Through the use of models and experience a set of future conditions that are to be achieved by resource manipulation is defined. Management actions in the form of goals, objectives, and plans for resource utilization are used to control and direct various environmental factors that affect the amount of production that can be achieved. Management decisions are implemented through the use of appropriate land management practices so that the intended managed state can be achieved. Depending on the scale of operations, evaluating the management options can become a complex job because of the number of possible alternatives.

RESOURCE ALLOCATION

In general, the process for managing a complex situation is to carefully define the system and then subdivide it into simpler component subsystems. In this way a system can be seen as a grouping of individual parts that operate together for a common purpose (Forester 1968). The framework that is developed provides a structured basis for thinking about the role of individual processes in terms of their respective contributions to the whole system.

Creating the conceptual framework for allocation of forest resources involves identifying a set of elements that are basic building blocks for decisions about allocation alternatives. Some of the elements will be controllable through the management decision making process and others such as weather, will be uncontrollable. Both the controllable and relevant uncontrollable elements will interact to produce the final outcome for a management alternative (Cleland and King, 1972).

Within the U.S. Forest Service planning process, there are five controllable elements which are manipulated to create possible management alternatives: (1) quantity of commodity outputs, such as water quantity, board feet of timber, animal grazing units, or recreation visitor days; (2) job quality which can be described by the kind, magnitude, and duration of non-commodity outputs as a result of implementing management practices; (3) locations for implementing management practices; (4) timing of management practices in terms of a sequence of entries and season of operation; and (5) changing the overall mix of kinds of commodities produced, based on the capabilities for production that were identified in the first four elements and social needs. In forest management, changing the mix of outputs may play a minor role in the decision process because of the problems involved in substantially changing an existing mix of available products.

A computer model, FORPLAN, based on a linear program is used to help evaluate forest resource outputs from specific land areas. Allocations for a particular management alternative are made by scheduling the use of resources among competing activities by using some criterion of optimality. Ecological limitations are incorporated into the model as constraints to ensure that the solution will be consistent with ecological capabilities of the land base (Kent 1980).

Management goals are chosen so that resource outputs, costs, and benefits can be evaluated at several output levels. Each resource output is described in terms of quantity, location, and timing. Quality is based on standards and guidelines which describe mitigating measures that are needed for resource conservation. The amount of a particular resource that is produced for a given management goal is dependent on its overall interaction with other resources that are also being produced.

Input data for the optimization model describes the amount, location, and environmental characteristics of existing resources along with data that collectively describe a range of future environmental conditions that could exist if management practices were implemented. Future conditions for each resource are based on a minimum requirement below which the resource cannot be allowed to fall because of constraints found in law, regulation, and/or scientific and professional expertise. The resource also has some maximum biological or physical level that cannot be exceeded. Integrating ranges of acceptable conditions for all resources creates a decision space that is bounded by the maxima and minima of the most restrictive resources. It is within this space that sound allocations of resources may be made (Williams and Warrington 1983).

PROCESS MODELS

Development of input data for an optimization model is aided by the use of models that simulate relevant environmental processes. Process models can be used to develop interpretations about cause-and-effect relationships of management practices over a wide range of environmental conditions. When developing these models, a balance must be obtained between the purpose of a model and attempting to account for all of the variation in a real system. Gold (1977) and Jeffers (1978) discuss procedures for modeling ecological systems.

During development, two characteristics of simulation models used for natural resource management need to be considered. First, the accuracy of a model should be compatible with an acceptable risk level associated with managing a resource. Risk can be expressed as the proportion of a resource output that could be accepted as a loss if the predicted effects are in error at some confidence level for the predictive capabilities of a model. The confidence level cannot be determined exactly but should be based on the possible management consequences of erroneously calling a true statement false (Type 1 error) or erroneously calling a false statement true (Type 2 error).

The second characteristic is that management-oriented resource models must be capable of operating with data that are readily obtainable from traditional sources or through monitoring conducted with simple techniques and equipment. In addition, the amount of unexplained variance that is acceptable in a management situation is often greater than would be acceptable in a research

environment. Modelers therefore need to evaluate carefully a models output for the information content that can be accounted for by a particular set of input variables. At some point during the development, adding variables will only provide diminishing improvements in a model at the expense of more complex data requirements.

One example of a management-oriented process model is a soil water balance model, that has been developed for U.S. Forest Service use (Warrington et al. 1983). This computer model simulates average monthly soil water regimes for forest and range sites producing information about potential soil water conditions and trends. Tables and graphs are created that can be used to plan the kind, location, and timing of forest practices to coincide with appropriate soil water conditions.

Soil is a short-term water storage component of the hydrologic cycle; therefore, the amount of water available to the plant is constantly changing. At any time the actual soil water content depends on the amount of water remaining from a previous period (antecedent water), the amount of precipitation that can become stored water, and the amount removed through evaporation, transpiration, and drainage. Processes affecting soil water content are simulated through three interacting subsystems using data about soil, climate, and site characteristics (fig. 1).

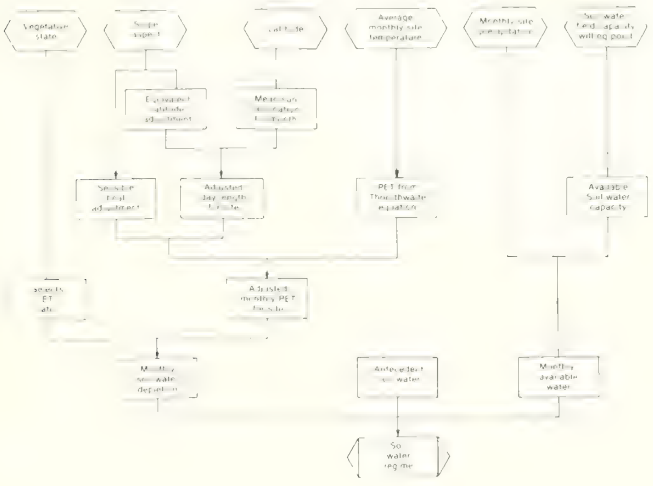

Figure 1.--Soil water balance model illustrating subsystems and relationships in a process model (Warrington et al. 1983).

The three general types of data used in this model are: (1) soil water content at field capacity and wilting point for each soil horizon; (2) average monthly temperature and precipitation for climate; and (3) latitude, slope, aspect, and vegetative cover condition for site characterization. Although other factors contribute to variations in soil water content, they only provide small increases in the models accuracy at considerable expense.

SUMMARY

Forest productivity depends on how natural resources are allocated for use and the yield of individual resources. At least two kinds of modeling approaches seem to be useful in the analysis process used to create management information about productivity. Information characterizing various aspects of production suitability and capability can be created from basic data through the use of models simulating environmental processes. Developing mixes of resources outputs for various management alternatives can be facilitated through the use of optimization models.

The models used in forest management are a set of tools that can be used to create information about the management characteristics of forest resources. These models should be developed from an analysis of management information needs and focus attention on the relationship among individual parts within the system being investigated. The formal models that evolve from this analysis process can be used to explain, predict, and show ways to manage the overall behavior of forest resources in order to produce desired outputs.

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ULTIMATE FOREST PRODUCTIVITY: WHAT IS POSSIBLE?

Bjorn Axelsson

ABSTRACT: As a result of some new fertilization experiments it has been shown that the productive capacity of forests may be several times greater than previously believed. The real potential and future management options are still unknown, but the potential dry matter production of forests exceeds that of most agricultural crops. In areas where nitrogen is the principal limiting element, forest productivity can be predicted with the aid of the nitrogen productivity concept. This concept takes into account not only the nutrient influx, but also the influence from light conditions and water as limiting growth factors. Also, the maximum leaf biomass for any stand can be predicted. Among opportunities for improving productivity, increased availability of nutrients seems to be the real challenge.

INTRODUCTION

As the ever-growing demand upon the earth's natural resources itensifies, improving the productivity of land becomes increasingly important. This has long been recognized in agriculture, but in regard to forests, which cover 50 percent of the land, the real potential has rarely been assessed. Current practices reflect, in general, only what managers believe will yield an economically valuable product. The real potential and future management options are still unknown (Boardman and Simpson 1981). As a result of a few small, but carefully designed experiments, scientists have discovered that the productive capacity of forest lands, even those in harsh climates, may be two to three times greater than previously thought. The assessment of economic alternatives must await future developments in technology and further experimentation on a larger scale. There is no doubt, however, that the options are greater than most of us had ever dreamed.

In this paper I will review the evidence for the greater potential with particular reference to the forests of northern Europe. Specifically, I shall discuss the opportunities for improving productivity through modification of (1) the availability of nutrients, (2) water, and (3) light by intensive silviculture, including the selection of genetically responsive varieties of trees.

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NUTRIENT CYCLING

Historical Background

A broad overview of nutrient cycling and forest productivity has been given by Tamm (1979); therefore, only some aspects of tree nutrition and forest nutrient cycling, of special importance for the analysis presented here, need a brief historical résumé.

As pointed out by Tamm (1979), scientific progress in forest nutrition has been slow because only a few of the researchers have also been interested in nutrient cycling and most research has been comparative rather than experimental. Only in the last decade have experiments provided a more functional understanding of ecosystems. At the beginning of this century, however, Hesselman (1917, 1926) made extensive studies of nitrogen mineralization attempting to develop a bioassay method to characterize the ability of the soil to supply nutrients, especially nitrogen. In the 1930s, Romell (1932, 1935) illustrated that bioassay methods were unsuitable for assessing nutrient mobilization in forest soils. In collecting soil samples, conditions were changed for the microorganisms active in decomposition. Mitchell and Chandler (1939) introduced foliar diagnosis from a different perspective. Their approach was to determine experimentally the nutrient requirements of different tree species based upon the growth response in relation to foliar nitrogen concentrations in several series of nitrogen dosage experiments. In an attempt to avoid some of the criticism that could be directed toward the approach of Mitchell and Chandler (Tamm 1964 p. 144) a series of so-called optimum nutrition experiments were started in the 1950s in Sweden by Tamm (1968). By applying nutrients annually the aim was to study growth in coniferous stands with controlled nutrient regimes, particularly for nitrogen, the principal limiting nutrient element in Europe (Tamm 1979) and parts of the United States (Gessel et al. 1965). Nutrient concentrations in the needles were determined in autumn. Whether needle nitrogen concentration in autumn reflects the critical time was a question.

The investigators' preference for sampling during the dormant season was criticized by Waring and Youngberg (1972). They recommend, along with Smith et al. (1970), that the "best time to characterize the differences in nitrogen is during periods of rapid growth when the demands for nitrogen are large." There are also studies suggesting that optimum nitrogen values may vary with age (e.g., Miller et al. 1981). Also, both Aronsson and Elowsson (1980) and Smith et al. (1981) have demonstrated that major errors in interpretation are likely if foliar analyses are expressed as a percentage of dry weight because carbohydrate contents vary seasonally. In many nutritional studies, foliar analysis as usually performed may, therefore, be of little diagnostic value. To interpret nutritional limitations to productivity, a dynamic description of the amounts of nutrients cycled within the whole system may be necessary (Ingestad et al. 1981, Tamm 1964) or at least through critical parts of the vegetative system.

Optimum Nutrition - Theory

Ingestad (1977, 1982) has challenged the conventional assumption of an optimum level. Rather, he suggested that the mineral uptake must be exponential during the exponential period of rapid growth and the mineral flux, rather than concentration of nutrient solution, is critical. Axelsson (1982) has suggested that the growth response may be extremely sensitive to how nutrients are supplied. A single large dose means decreasing concentration over time and a typical "diminishing return" growth curve, while nutrients supplied at a rate matching plant needs gives an almost linear response (fig. 1).

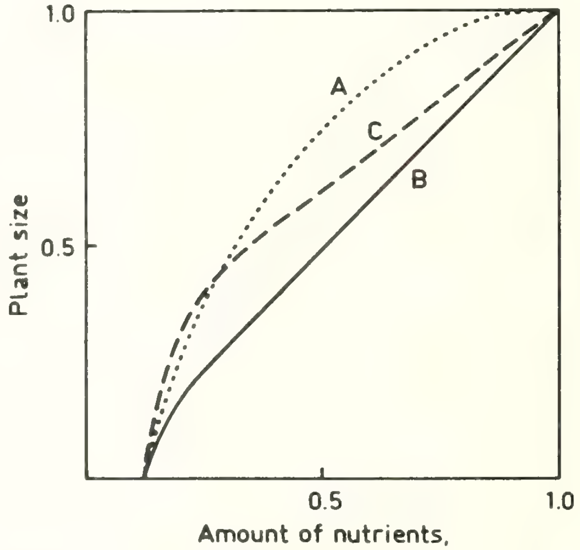

Figure 1.--Theoretical growth curves in plant nutrition experiments: (A) decreasing nutrient status in plant, (B) plant nutrient status kept constant, and (C) increasing nutrient status. From Axelsson (1982).

Ingestad (1982) found that a certain nutrient flux density, up to a limit, resulted in an increasing productivity. There was no growth plateau, but an abrupt drop. It must be emphasized, however, that the results refer to laboratory experiments with tree seedlings growing exponentially. The seedlings were maintained at steady state nutrient status and relative growth rate.

An additional contribution to research in this field is a study by Linder and Rook (1982) showing that seedlings in steady state have linear relations between limiting nutrient flux and photosynthesis and respiration. They also illustrated via simulation that if the seedlings are not in steady state, more rapidly growing plants will have much lower nutrient concentrations than plants constrained to grow more slowly

but supplied with the same amount of minerals per plant per day. Growth was constrained by reducing irradiance levels (fig. 2).

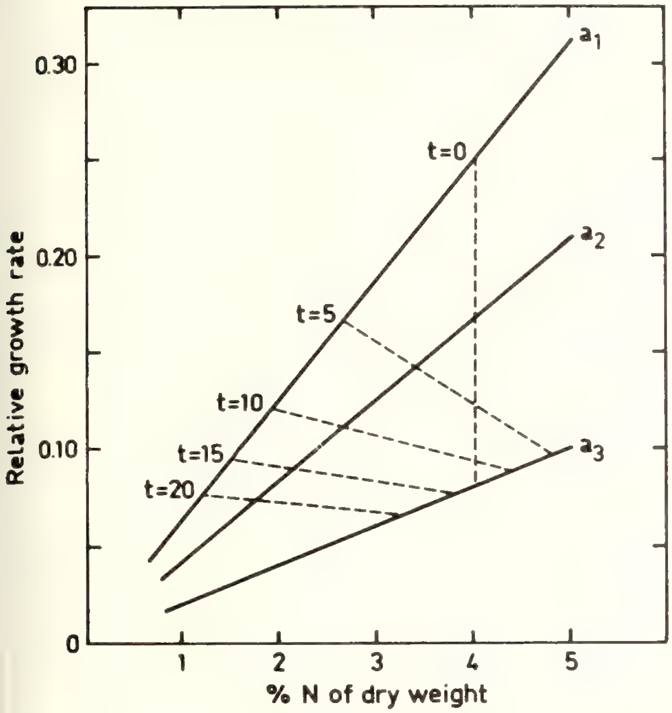

Figure 2.--The effect of constant nitrogen supply, 1 mmol day^{-1}, on nitrogen concentration and relative growth rate of Betula pendula seedlings with different nitrogen productivities (a). Initial plant weight 2-g dry weight, initial nitrogen concentration 4 percent of dry weight and simulated time in days (t). In this simulation three different values of nitrogen productivity (via different irradiation levels) were chosen, corresponding to three relative growth rates. Nitrogen productivity defined according to Ingestad (1979). The nitrogen supply rate was suboptimal at the high and medium growth rates to maintain a constant relative growth rate resulting in decreased internal nitrogen status and relative growth rate with time. The plants from the most favorable growing conditions became the biggest at the end of the experiment and showed the lowest internal nitrogen concentrations, thus a negative correlation between plant size and internal nutrient status. From Linder and Rook (1982).

These results have direct implications for plants growing under field conditions. The amount of biomass produced per unit of time and unit of nitrogen (i.e., nitrogen productivity (Ingestad 1979)) is likely to be a good index to forest productivity according to Agren (1983a).

Application of Nutrient Flux Theory to Forest Stands

Tree stands differ from seedlings growing under laboratory conditions in several respects: self-shading in the canopy, redistribution of nutrients within the trees, competition for nutrients among trees, lesser vegetation and microorganisms (Tamm and Aronsson 1983). Still it is difficult to quantify these relations into a theory on forest dynamics. Lindgren and Axelsson (1980) attempted to model the long-term development of a Scots pine forest but found that lack of quantitative data regarding competition for nutrients within the forest ecosystem made the model unstable. More research is therefore needed, particularly concerning competition for resources. Ingestad et al. (1981) presented a simple model in which the nutrient flux is divided into two parts, one delivered by mineralization and the other by fertilization. The model can therefore be used to analyze the dynamic effects of both nutrient sources as well as interactions between fertilization and the natural nutrient flow upon the fertility level of the ecosystem. Contrary to most studies of forest tree nutrition, it is the amounts of nutrients incorporated in different organs that is critical, not the concentration.

The nitrogen productivity concept as a forest productivity index was further analyzed by Agren (1983a, 1983b). His concept allows the growth of a forest stand to be predicted rather than the growth of individual trees. The formulation is:

$$\frac{dW}{dt} = P_{(N)}N - fW \qquad (1)$$

where W is the amount of biomass (for simplicity here equal to total needle biomass), N is the amount of nitrogen in the biomass (needle mass), $P_{(N)}$ is nitrogen productivity, and f death rate. As a first approximation, f is taken as a constant (further examined below). Then it follows from equation(1) that if $P_{(N)}$ also were constant, the forest would increase indefinitely by cycling more and more nitrogen. Obviously forests don't respond this way, so the most likely explanation is that nitrogen productivity decreases with increasing stand biomass. It seems reasonable to correlate this decreasing trend with self-shading, water stress, and perhaps reduced nutrient flux (Agren 1983a, Axelsson 1982, Bradford and Hsiao 1982). The simplest hypothesis is to assume a linear decrease in $P_{(N)}$ with biomass:

$$P_{(N)} = a- bW \qquad (2)$$

where a and b are two parameters. The forest biomass W_m thereby assures an upper bound:

$$W_m = \frac{a- f/(N/W)_m}{b} \qquad (3)$$

where $(N/W)_m$ is the optimal nitrogen concentration (Ingestad et al. 1981). Values for four parameters have to be estimated to predict the maximum biomass in a forest stand.

Field Data Supporting Theory

The examples presented next will only refer to stand needle biomass. There is a strong

relationship between leaf biomass and production of other tree organs that makes it fairly easy to estimate total production of the tree or forest. As pointed out by Agren (1983a), the rapid turnover of the leaves should make them responsive to changing conditions. In his analysis (Agren 1983a) it was possible to find adequate data only for Picea abies Karst., Pseudotsuga menziesii (Mirb.) Franco, Pinus sylvestris L., Pinus nigra var. maritima (Ait.), and Pinus resinosa Ait. that covered a wide range of ages, stand densities, soil conditions, and geographical locations. From a statistical point of view, only Scots pine and Norway spruce were adequately sampled, but the overall results support the basic idea (fig. 3). The data for Scots pine was gathered from Sweden, Finland, and England and the spruce data represented Sweden, Germany, Czechoslovakia, and the U.S.S.R. The analyses indicated a maximum needle biomass on the order of 11-18 metric tons for the pine species, 28 tons for the spruce, and an intermediate value for the Douglas-fir of 22 tons (dry weight) per hectare. These maximum biomass figures are, of course, dependent on the parameter values used in the calculations. For example, death rate was estimated from the ratio between current needles and total needles which is appropriate in a steady state condition, but represents an overestimate of parameter f in a stand with expanding canopy. The analysis of the primary data, however, showed a fairly small variation. As an example the needle death rates in different Scots pine stands (fig. 4) change the estimates of maximum needle biomass by about 25 percent. Thus even fairly small differences in death rates of needles may have significant consequences. A decreasing f-value means an increasing maximum needle biomass and, indirectly, a decreasing nitrogen productivity. On the other hand, a low rate of needle mortality means that more of the total nitrogen pool within the tree-soil system is contained in the canopy, leading to increased production. There are data indicating that the f-value is age-dependent and further there seems to be an increase in f from northern Sweden through central Sweden to England. If true, good estimates cannot be made of the maximum biomass by studying young stands. Also, if the f-value is climate dependent, the Scots pine growing in northern Europe under a cooler climate may compensate partly by being more efficient in utilizing nitrogen (fig. 4) and having lower maintenance respiration for non-photosynthetic tissue.

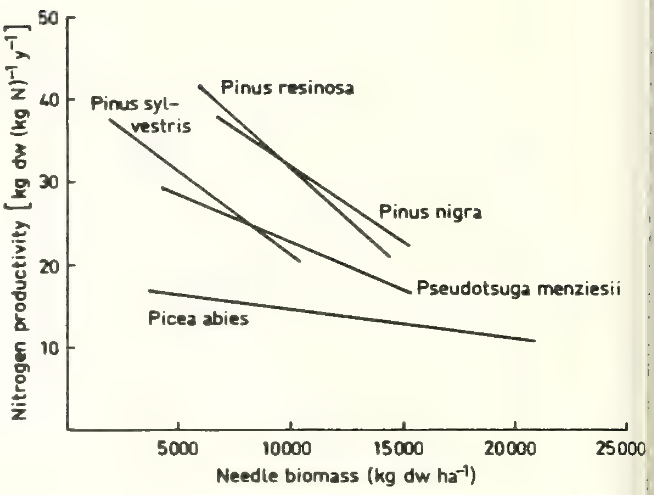

Figure 3.--Nitrogen productivity for some conifers based on data from a wide range of ages, stand densities, soil conditions, and geographical locations in U.S.S.R., western Europe, and North America. From Agren (1983a).

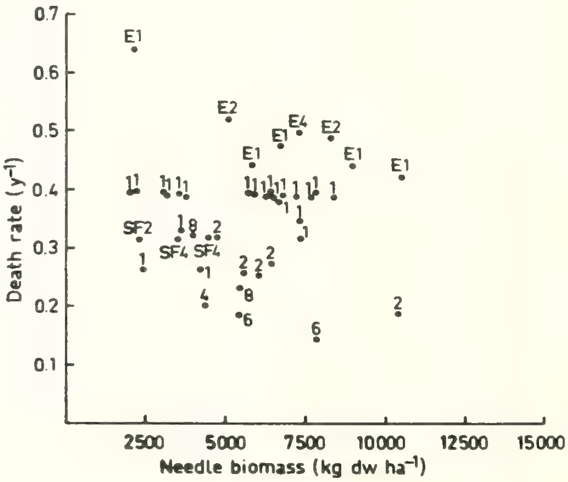

Figure 4.--Death rate of Scots pine (Pinus sylvestris L.) needles, estimated from the ratio between current needles and total needles. This is reasonable in a steady state condition, but means an overestimate in expanding stands. Data from: (E) = Ovington 1957, (SF) = Malkonen 1974. Others from central Sweden. Stand age-class is indicated where: (1) = $\leq$ 20 years, (2) = 21-40 years, (4) = 41-60 years, (6) = 61-84 years, and (8) = > 85 years.

TREE WATER BALANCE

Water is supposed to be of minor importance in humid parts of northern Europe. This is most likely the reason for so few studies in water relations as compared to fertilizers. Nevertheless, the effect of climatic factors on growth of forest trees has been studied for over 70 years in Scandinavia (Hesselman 1904a, 1904b). Research workers have found a correlation between temperature and growth; but moisture and rainfall

have had an effect only on drier sites in southern parts of Scandinavia and in the north, only in dry years (Mikola 1950). Towards the south, precipitation therefore becomes a more important and limiting factor. There could be a break-point between the dependence of temperature and precipitation on stem growth in about the middle of Sweden (Kolmodin 1935). In middle and northern Sweden, irrigation improved Scots pine stem growth 20 percent and 10 percent, respectively (Aronsson and Tamm 1982, Axelsson 1981). In Denmark, Holstener-Jørgensen et al. (1979) have demonstrated a 20-30 percent increase of needle mass by Picea abies in an irrigation-water stress experiment. Miller et al. (1977) reported reduced growth following drought in a mature stand of Scots pine in Scotland. However, improved supplies of water may also stimulate decomposition and mineralization.

From extensive ecophysiological studies, Linder and Troeng (1980) have shown that annual photosynthesis in young (15-20 years) Scots pine was independent of normal variation in precipitation in mid-Sweden. Agren and Axelsson (1980), however, found that annual carbon budgets for mature Scots pine stands had a surplus of photosynthetic products unless the assimilation was reduced by tree water stress. In large Scots pine trees, preliminary data indicate a 30-50 percent reduction in photosynthesis caused by low turgor associated with necessarily higher water potential gradients through the stem (fig. 5).

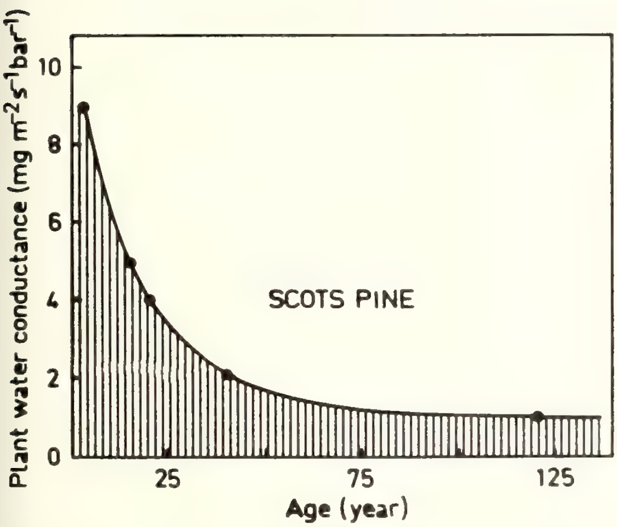

Figure 5.--Water conductance decreases with increasing tree size (age). Photosynthetic production is not influenced in young Scots pine trees, but in the mature forest this process can be strongly reduced by water stress. From Mattson-Djos (1982).

Obviously, the nutrient cycle is affected by the water regime which in turn depends on climate, topography, soil depth, etc. The differences in site quality among ridges, slopes, and valley bottoms are usually ascribed to differences in water supply and aeration (Tamm 1979). Even very small differences in topography may have a significant effect on water regimes (fig. 6). The site, situated in mid-Sweden on till, together with the design of an irrigation-fertilization experiment with Scots pine and Norway spruce, are described elsewhere (Axelsson 1983). In figure 6, three plots with Scots pine (1, 6, 7; July data) are below the predicted production level. All had significantly higher soil moisture content early in the growing season, which was associated with small differences in topography. Preliminary studies of the water balances in the trees support the hypothesis that a shallow ground water constricts root development and results in stress during the dry summer periods and could lead, consequently, to a reduction in nitrogen productivity. The general agreement between predicted and measured needle biomass on the different plots (fig. 6) supports the nitrogen productivity concept and also the importance of sampling during the growing season when the nutrient status is most critical (Axelsson 1983).

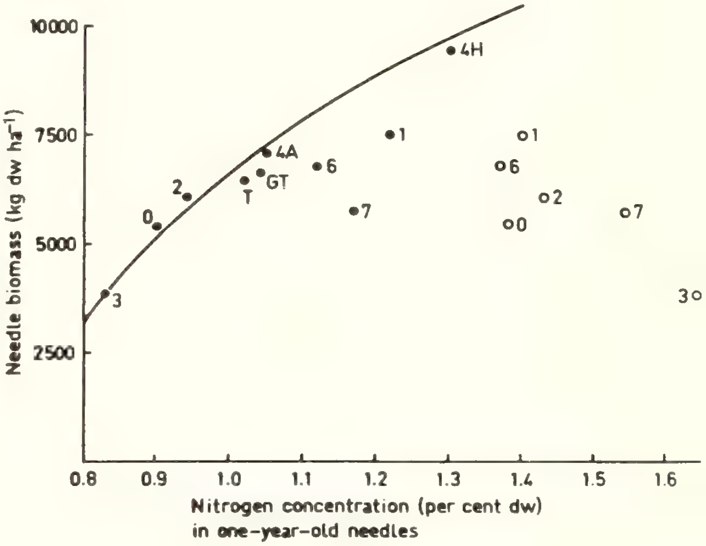

Figure 6.--Stationary needle biomasses as a function of nitrogen concentration in the needles predicted by the aid of the nitrogen productivity concept (curvilinear relationship) and field data from Framlingshem experimental area, 1981. Foliar diagnosis July 14 (filled symbols) and April 7 (open symbols), 1981. Figures 0-7 refer to experimental plots. From Axelsson (1983).

INTERCEPTION OF RADIATION

Blackman and Black (1959) reported that differences in the levels of net assimilation rate and relative growth rate are positively correlated with insolation, but Kamiyama and Horie (1975) found that neither net assimilation rate nor

relative growth rate was closely correlated with radiation when they extended the approach to other crops and climates. Arable crops accumulate dry matter during early growth in proportion to the actual absorbed radiation not the total radiation (Monteith 1981). Perhaps this helps explain the lack of consistency in correlations between forest production and total radiation. It is also relevant to stress that crop yields depend on the length of the growing season and that the fraction of intercepted radiation is not proportional to leaf area index except during very early growth. Consequently, the net assimilation rate or the relative growth rate changes periodically during the growing season (Monteith 1981). Differences of yield from year to year are seldom correlated with light. Potential yield correlates with the rates at which leaves grow and die; actual yield is reduced further by such factors as drought, disease, etc.

POTENTIAL PRODUCTIVITY

In view of the wide differences in site properties, it is rather surprising that actual annual dry matter production by trees and the majority of agricultural crops are often similar--on the order of 5 metric tons per hectare per year in northern Europe (Jarvis 1981). A rate of dry matter production of 5 $t.ha^{-1}.yr^{-1}$ is only 10 percent of the potential production (net rate of photosynthesis) that could be achieved by a (C_3) crop; i.e., 54 $t.ha^{-1}.yr^{-1}$ (Monteith 1977). The maximum rates of annual production of forest crops, however, are also up to an order of magnitude larger than the rates achieved under normal management practice (Jarvis 1981); but almost all maximum rates are reported from small research plots. Particularly high rates, however, have been reported for large stands of coniferous forests in Japan, New Zealand, and the Pacific Northwest (Benecke and Nordmeyer 1982, Grier et al. 1981, Kira 1975). Ovington (1962) also estimated the maximum net rate of current annual dry matter production by coniferous forests in western Europe at 22 $t.ha^{-1}.yr^{-1}$ with a corresponding figure for maximum mean net production over the life of the crop of 15 $t.ha^{-1}.yr^{-1}$. Recently, Tamm and Aronsson (1983) concluded that "as far as known, no other ecosystem than the optimum fertilized spruce plots has been found to produce as much dry matter (of needles, branches, and stems) as 10 to 12 metric tons per hectare and year under similar climatic conditions" (middle Sweden, lat. 61° N., altitude 350 m). One of the highest values reported for coniferous forests in the temperate zone was from a 17-year plantation of Sitka spruce in Scotland, namely 26.7 $t.ha^{-1}.yr^{-1}$ of net annual aboveground dry matter production (Ford 1982).

Very few reliable estimates are available on root growth and turnover in coniferous stands, but some recently published indicate that root growth may be equal to or even exceed the total aboveground production of leaves, branches, and stems (Agren et al. 1980, Axelsson 1981, 1983, Grier et al. 1981, Harris et al. 1977, Persson 1983). For Scots pine 50 percent of annual net production may be allocated to root production in 20-year-old stands. In older forests or after fertilization of young stands only about 30 percent may go to roots (Agren and Axelsson 1980, Axelsson 1981, Linder and Axelsson 1982). We should, therefore, add at least 30 percent to the quoted production rates for coniferous forests growing in western Europe.

Linder and Lohammar (1982) have made calculations, based on either empirically derived production data and measurements of incoming radiation or photosynthetic response to light as determined in the laboratory, that predict a maximum forest net biomass increment of 34 $t.ha^{-1}.yr^{-1}$ of leaves, stems, and roots in southern Sweden. Of this, one third was root production, around 20 t were stem and branch wood, and leaf production was 3 t, corresponding to a leaf area index of 5.

Linder and Lohammar conclude that maximum yield in biomass production is 15-20 $t.ha^{-1}.yr^{-1}$ in central Sweden and 10-15 t along the Bothnian coast. Although these predictions concern energy forests (<u>Salix</u> spp.), they may also be valid for Scots pine since photosynthetic capacity is about the same (Troeng and Linder 1982). One conspicuous difference between the energy forest and the pine forest is, however. that the same leaf area index (e.g. LAI=5) means 3 tons of leaves but 15 tons of needles. Jarvis (1981) argues that the reason for the high assimilation rate in the conifer canopy is "the effective distribution of intermediate flux densities of radiation throughout the foliage, as a result of grouping of the needles, the small size of the needles and the ability of the needles to utilize effectively low light received on each surface." Another main reason for high production is the retention throughout the year of a considerable leaf area, which is of particular importance in temperate, oceanic climates where photosynthesis is possible for a major part of the year.

At present, opportunities to increase production through genetic selection appear relatively small compared with the immediate gains likely through improving the availability of nutrients. Also new species are not without problems. But an additional 30-50 percent in harvestable material might be obtained realistically with careful selection of adapted species or genotypes (Ekberg et al. 1983). Direct cloning of superior individuals might give gains of 50-100 percent (Nienstaedt and Jeffers 1976).

CONCLUSION

The potential dry matter production of forests exceeds that of most agricultural crops. To more accurately evaluate the potential of conifers, a series of experiments throughout Europe are recommended with optimum supply of fertilizer and water. Recent experience in fertilization experiments in Sweden indicates that a potential gain of two- to fourfold is possible above conventional harvests. On the basis of both theory and experimental evidence, present management

practices apparently fail to supply nutrients to trees in sufficient amounts. In nutritional studies, foliar analysis may not be adequate to interpret nutritional problems, particularly if the diagnosis is restricted to times of low nutrient demand. In principle, a dynamic view of the amounts of nutrients cycled throughout the system during the growing season is more likely to provide better evidence of nutritional status. The nitrogen productivity concept takes into account not only the nutrient flux but also the influence from light, climate and water as limiting growth factors. By combining foliar diagnosis with studies of leaf biomass dynamics and allocation, the maximum leaf biomass for any tree stand can be estimated. Being able to estimate the difference between actual and potential productivity will be very important to forest managers.

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ULTIMATE FOREST PRODUCTIVITY IN NORTH AMERICA

Gordon F. Weetman

ABSTRACT: Full stocking and appropriate stand conversion, along with thinning, genetic improvement, and better utilization, will achieve greatest increases in North American forest productivity, but the removal of site constraints, particularly nutritional ones, also has great potential for yield improvement. Concepts and problems are reviewed in range limitations, movement of the ecological niche, expression of regional biological optimum production, growth and yield concepts, and site improvement. Nutritional problems and concepts are reviewed in more detail. Appropriately timed and dosed additions of N have great potential to approximate optimum stand nutrition; some examples are given. Stand testing must proceed empirically since the processes of stand N-mineralization, immobilization, and uptake are poorly understood. While simulations of N transfers are possible, validation is difficult in the absence of accurate techniques of measurement. More optimum nutrition trials and more basic scientific research on the N cycle in forests are needed.

INTRODUCTION

The biological productivity of United States forests has been reviewed by Spurr (1976). He looked at intensive biomass management and increased utilization (table 1). The potential for improvement is great on about 200 million ha. Reed (1978) looked at potential Canadian yield increases. He estimated 0.1 to 3.3 $m^3.ha^{-1}.yr^{-1}$ increases due primarily to better regeneration. The productive forest area in Canada is about 235 million ha.

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This paper will be restricted to the site component of ultimate productivity; genetic improvements, stand conversion, full stocking, and thinnings that have the greatest potential nationally for yield increases will not be considered.

Site improvement, particularly fertilization, is like icing on a cake--often the final step when a good job of silvicultural baking has been done. It is no coincidence that interest in achieving ultimate productivity by site improvement in North America is largely restricted to areas with intensive management programs in place. Over much of the United States and Canada a huge task of basic silviculture is yet to be done. Spurr

Table 1--Biological productivity potential of United States forests, including cumulative effects of various silvicultural and utilization practices on mean annual productivity (Spurr 1976)

	$ft.^3 \cdot ac^{-1} \cdot yr^{-1}$	$m^3 \cdot ha^{-1} \cdot yr^{-1}$
Actual growth (500 million acres)	38	2.6
All lands fully stocked	74	5.2
Fertilization, drainage, site improvement (50 million acres)	75	5.2
Stand conversion (30 million acres)	77	5.4
Genetic selection (3 million ac/yr)	83	5.8
Thinnings	104	7.3
All aboveground biomass used	148	10.3

assigned almost negligible improvement in national forest productivity because of site improvement. He assumed that 50 million acres were treated to increase growth by 15 percent giving an average improvement on all lands of only 1.5 percent.

Spurr (1976), using estimates from Gessel, Steinbrenner, and Bengston, suggested about 7 million ha along the north Pacific coast and 1.6 million ha along the southern coastal plain could be fertilized with N and P, respectively. Fertilization in Canada is currently restricted to the Douglas-fir coastal region. While response to N has been shown in boreal forest testing programs (Krause et al. 1983, Morrison 1982) commercial scale fertilization is unlikely until other higher priority silvicultural problems, such as adequate regeneration, are solved and until more silvicultural incentives are provided in the lessee/lessor relationship on provincial Crown lands.

RANGE LIMITATIONS

The opportunities for dramatic improvements in productivity by using exotic species appear to be limited with the notable exception of eucalyptus in the southern United States. The ice age left a rich reserve of tree species in North America. In Europe the ice age wiped out some species. America is a famous exporter of tree species to Europe. European foresters know more about some Pacific Northwest species in plantation culture than do foresters in the United States and Canada. Monterey pine and slash pine have produced dramatic yield increases when planted as exotics (Wright 1976).

Opportunities for yield increases through provenance tests are real. Species migration to the north is still occurring; however, the yield increases are yet to be proven. We foresters are conservative in the movement of tree species. The best use of species must be made within their natural range. They are arranged along site gradients of moisture, nutrients, and temperature, each occupying its ecological niche.

ECOLOGICAL NICHE MOVEMENT

Each species can be located along the environmental gradients; each is different in ecological amplitude and competitive ability. Using artificial regeneration species can be moved to richer sites and/or wetter sites, but the species may be noncompetitive; i.e., they may require much tending energy to hold them there. It can be done horticulturally. Unknown environmental risks such as insects and disease may also be incurred. Even so, species have been moved to richer sites on a large scale; e.g., pine on spruce sites. Spruce planted on hardwood sites in Europe has historically produced some dramatic yield increases; e.g., Norway spruce in Czechoslovakia where 80 percent of the hardwood forest was converted, but now a price in ecological stability may have to be paid. Reproduction costs may be high. Moving southern pines onto southern hardwood sites may yet produce some nasty surprises. High-risk, high-yield plantations on rich sites with high energy input silviculture is appealing. Can the high yield be achieved with less effort? Realistically most forests are and will be composed of species in their natural niches.

EXPRESSION OF REGIONAL BIOLOGICAL OPTIMUM PRODUCTION

Within an ecological zone or region the "best" sites are "normal" or "mesic"; i.e., are midpoint in a three-dimensional box of nutrition-, moisture-, temperature-ranked gradient values (fig. 1). The sites are not too hot or cold, dry or wet, or rich or poor. Such "normal" sites are real and can often be found. They have been used to rank production and estimate yield potential for regions for fully stocked, mature, virgin forests in Canada; e.g., in British Columbia and Ontario.

The three-dimensional box is filled with tree species like ping-pong balls of different sizes (fig. 1). The ecologically "best" site is associated with one or two major tree species best suited (i.e., most "fit") for both pioneer and later successional conditions.

The natural occurrence of pioneer species on these sites may not be economically attractive ones; e.g., red alder in the Pacific Northwest or poplar in the boreal. Very few sites are "normal"; most deviate widely from the regional optimums of moisture, nutrients, and temperature.

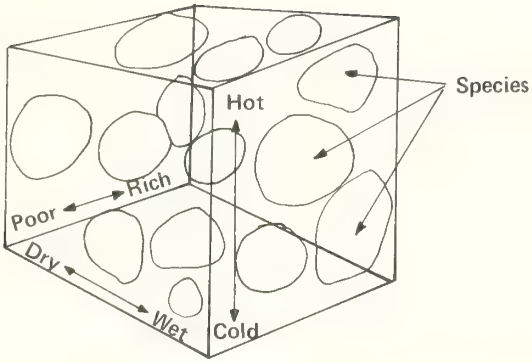

Figure 1.--Schematic representation of environmental effects on species distribution.

Historical fires have often resulted in aggressive pioneer species of wide ecological amplitude and low competitive ability (like poplar) occupying a whole gamut of sites.

Trying to find the normal site, occupied by the desired species expressing the ultimate regional productivity, is an exercise done by all foresters. Rarely can the combinations of species on normal sites be found. When some impressive productivities are found--site I or Ia for the species--height/age is used as the expression of site.

For North America, evergreen trees growing in northern California or southern Oregon on deep, well-weathered permeable soils with a long growing season, ample precipitation, cool winters, represent the ultimate in natural productivity (Haddock 1982)1/.

For the Pacific Northwest, site indexes for regional species are compared with those of the same species in other climates; e.g., Douglas-fir in New Zealand, the United Kingdom, France, and Germany; grand fir in Europe; and Sitka spruce in the United Kingdom and Norway. The problem in these comparisons is that apples and oranges are being compared--or more exactly, intensively managed stands versus natural second-growth or old-growth forests. This raises the question of how to express ultimate productivity.

GROWTH AND YIELD CONCEPTS

The correct technical term for expressing ultimate productivity is net primary production (NPP), i.e., what is left after respiration.

NPP = Le + Br + S = R, i.e. the annual production of leaves, branch wood and bark, and stem and root wood and bark. If mortality and grazing are ignored (they are usually small), then NPP = B + L + G, where B is the sum of Br, W and, R; L is litterfall including mortality; and G is grazing loss to herbivores. This latter formula is better for older stands with mortality.

Using these formulae, Grier (1976) found that western hemlock on the Oregon coast apparently not suffering from nitrogen or moisture limitations, produced 1.2 kg of biomass per unit foliage. The total NPP was 37 750 $kg.ha^{-1}.yr^{-1}$ for the 26-year-old stand. For a tolerant conifer growing under close-to-ideal conditions, before wind or storm losses, this value is probably close to the ultimate because of the favorable growing conditions.

Of this value, 25 000 $kg.ha^{-1}.yr^{-1}$ was stems and branches and at 409 kg/m^3 this is 61 $m^3.ha^{-1}.yr^{-1}$. The annual growth requirement for N was 129 kg or 2 $kgN.m^{-3}.yr^{-1}$. Other values for high-site, aboveground NPP in Douglas-fir and western hemlock ranged from 4 000 to 10 000 $kg.ha^{-1}.yr^{-1}$ or about 10 to 24 $m^3.ha^{-1}.yr^{-1}$.

Grier's 121-year-old western hemlock produced 7 400 $kg.ha^{-1}.yr^{-1}$ of stem and branches requiring 40 kgN - or about 2 $kgN.m^{-3}.yr^{-1}$. This approximate value is of interest when looking at fertilizer N efficiencies.

Unfortunately, trees are not conventionally measured in biomass terms and in practice the concern is only with stemwood production in $m^3.ha^{-1}.yr^{-1}$--and then only in economic sizes. Some of the recent enthusiasms for biomass production have been dampened by the high cost of its collection for use and the current collapse of the oil supply crisis.

European yield tables give us gross and net yields for plantations assuming certain thinning regimes to recover mortality. These tables are based on real plot measurements. United Kingdom normal yield tables give 23 $m^3.ha^{-1}.yr^{-1}$ for mean annual increment for yield class 24 for both western hemlock and Douglas-fir (Hamilton and Christie 1971).

North American yield tables, lacking long plot remeasurement records, are a little less real. This does not deter the biometricians equipped with computers, but gross yields (i.e., full recovery of mortality) is less certain. Wiley (1978) gives gross mean annual increment (m.a.i.) for western hemlock site index 37 m at 50 years of about 29 $m^3.ha^{-1}.yr^{-1}$.

The technical effect of increasing productivity is to increase the yield class or site productivity. Theoreticians in the biometrics field suggest that the processes of stand development are accelerated but not changed in character (Harper 1977).

Widespread use is made of Reineke's (1933) stand density index, or its more modern embodiment the $w = cp^{-3/2}$ or 3/2-power law to express the

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1/ Haddock, P. G.; Personal communication, Faculty of Forestry, University of British Columbia, Vancouver, British Columbia.

remarkably constant relationship between the mean weight or size and density of survivors in a dense population. This law, which produces a species characteristic straight line when plotted log/log, holds for plant species. This species survival line for trees enormously simplifies complex density, yield, and mortality relationships. It permits the use of stocking guides.

Of importance is the finding that "variations in soil quality have the same effect as in the experiments with animals of moving points up and down a common thinning line, not shifting the position of the line" (Harper 1977); i.e., upping site quality drives the stand faster through its development stages. The size/density relationship is locked in.

From the practical point of view this allows foresters to use stand density control diagrams such as the one for Douglas-fir by Weyerhaeuser (Drew and Flewelling 1979). Yield is the product of mean tree volume x density, independent of site. Ultimate yield forecasting becomes possible when the rate of progress of the stand is known.

ADJUSTMENT OF LIMITING FACTORS

There are many opportunites to adjust limiting factors in attempting to reach ultimate productivity.

1. Foresters can match species to site to approach the regional optimum production. This is done based on local ecological evidence, but risk must be balanced versus costs and yields.

2. Foresters have opportunities to manipulate the genotype. Tree improvement programs, notably in southern pines, have increased yields, tree quality, and reduced risks. The yield increases are probably in the 15 percent range, but are attainable only with artificial reforestation.

3. Foresters cannot change regional climate, nor can they change soil moisture as a limiting factor except by using complete tillage, drainage or irrigation, practices that have limited economic feasibility for most forests.

4. Full site occupancy can be realistically achieved by control of stand density and competing plants. Minimum basal area levels are needed such as B-levels in stocking guides for even-aged stands, appropriate q values, and maximum diameters in uneven-aged stands (Hann and Bare 1977, Hann and Brodie 1980). These steps will ensure full site potential is utilized.

5. The most convenient way to increase site quality is by input of nutrients. If we ignore the rare occasional micronutrient deficiency, site improvement usually involves an addition of N or P or both; P mainly in the southern pine sandy soils where an interaction with drainage is important, N in most other places.

NUTRITIONAL PROBLEMS AND CONCEPTS IN ULTIMATE PRODUCTIVITY

Tamm (1979, 1980) has reviewed the role of plant nutrients as limiting factors. Recognition of these nutritional constraints in forests has been slow. It was easy in nurseries where exports were obvious, was readily apparent with litter removals in German forests, but less apparent in closed forests with considerable stores of nutrients and annual recycling.

The key controls are soil P status in southern pines and the store of N and rate of N mineralization elsewhere on mineral soils. The temporary nature of the N response is well known. The literature on fertilizer response is enormous except in the area of repeated and sustained response. It is speculated that responses to repeated applications of N fertilizer will occur as shown in fig. 2.

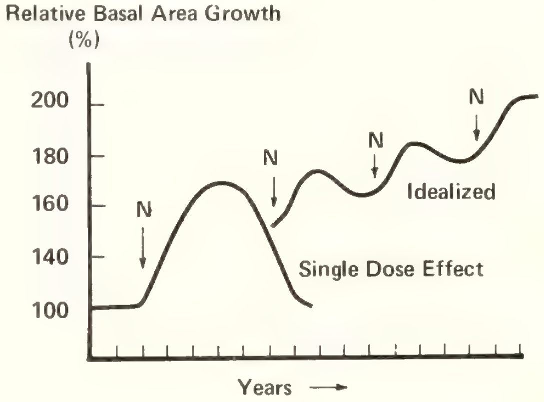

Figure 2.--Idealized responses to single and repeated applications of N fertilizer.

The concept of optimum nutrition was explored systematically in tree seedlings by Ingestad (1981), who developed ratios of foliar nutrient concentrations in relation to nitrogen that are widely applicable to trees. He has pointed out that:

> "the traditional experimental technique has produced some serious artifacts which are caused by a lacking correspondence between nutrient additions, carried out as concentration treatments, and the actual and exponentially increasing amounts of nutrients required by the plants. The internal nutrient status is therefore not maintained at stable state. The result is the classical nutrition/growth relationships: optimum curves between nutrient status and yield and Mitscherlich-curves between nutrient addition and yield indicating 'diminishing return' of nutrient addition. When nutrients are added as a relative addition rate, nutrient status and relative growth rate remain in a steady

state and strong linear relationships are found between relative addition rate and nutrient status, and between nutrient status and relative growth rate, which relationships are fundamentally different from the classical ones. As a consequence, growth rate per unit of nitrogen (N productivity) increases or is constant with increasing nitrogen addition or nitrogen status. Furthermore, maximum relative growth rate is sharply definable at saturation of the internal nutrient status beyond which a further increase of the relative addition rate has no growth stimulating effect."

Application of these universally balanced nutrient ratios to solutions for seedling nutrition in container stock has spectacularly improved stock production.

Application of the same concept in the forest is more recent. The idea is to provide optimum nutrition in the forest. The SWECON project in mid-Sweden Scots pine has done this. Tables 2 and 3 show some data from Axelsson (1981) for a forest irrigated with balanced nutrient solutions. Not only is the very large growth increase of interest in a harsh boreal climate, but also the apparent increase in efficiency due to much less production of fine roots.

Table 2--Annual biomass (DW) production in a 20-year-old Scots pine stand at Ivantjarnsheden, mid-Sweden percentage production, (Axelsson 1981)

Treatment[1/]	Needles	Branches		Stems	Stumps	Roots		Total
		current	old			coarse (>2mm)	fine (<2mm)	
	(%)							
0	19.1	2.6	8.7	12.7	2.7	13.2	17.5	100.0
I	18.0	5.4	14.3	15.0	4.0	8.0	35.0	100.0
F	24.4	6.7	13.9	15.1	3.3	19.1	41.0	100.0
IF	23.3	10.3	19.5	17.3	4.7	10.3	14.5	100.0

1/ 0 = control, I = daily irrigation, F = solid fertilization once a year, IF = daily liquid fertilization. Treatment period: late summer 1974-1979.

Table 3--Biomass (DW.) and relative productivity in a 20-year-old Scots pine stand at Ivantjarnsheden, mid-Sweden. All figures refer to 1979 (Axelsson 1981)

Treatment[1/]	Needle biomass	Stem biomass	Total annual prod. per needle biomass	Total annual prod. per N added	Needle prod. per N added	Stem prod. per N added	Stem biomass per needle biomass	Stem prod. per needle biomass
	(kg/ha)	(kg/ha)	(kg/kg)	(kg/kg N)	(kg/kg N)	(kg/kg N)	(kg/kg)	(kg/kg)
0	2310 (100%)	3036 (100%)	1.93 (100%)	--	--	--	1.31	0.25
I	2542 (110%)	3582 (118%)	2.06 (107%)	--	--	--	1.41	0.31
F	6408 (277%)	6867 (226%)	1.63 (84%)	21.8	5.3	3.3	1.07	0.25
IF	6777 (293%)	8835 (291%)	1.86 (96%)	14.5	3.4	2.5	1.30	0.32

1/ 0 = control, I = daily irrigation, F = solid fertilization once a year until 1979 480 kg N, 120 kg K, and 60 kg P per ha, IF = daily liquid fertilization, until 1979 870 kg N per ha, all other essential nutrients in proportion to N.

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NUTRITIONAL PROBLEMS AND CONCEPTS IN ULTIMATE PRODUCTIVITY

Tamm (1979, 1980) has reviewed the role of plant nutrients as limiting factors. Recognition of these nutritional constraints in forests has been slow. It was easy in nurseries where exports were obvious, was readily apparent with litter removals in German forests, but less apparent in closed forests with considerable stores of nutrients and annual recycling.

The key controls are soil P status in southern pines and the store of N and rate of N mineralization elsewhere on mineral soils. The temporary nature of the N response is well known. The literature on fertilizer response is enormous except in the area of repeated and sustained response. It is speculated that responses to repeated applications of N fertilizer will occur as shown in fig. 2.

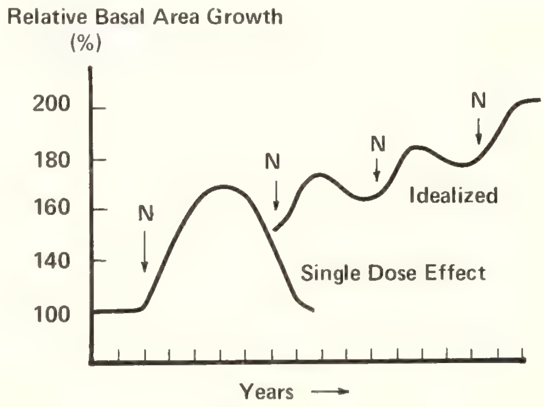

Figure 2.--Idealized responses to single and repeated applications of N fertilizer.

The concept of optimum nutrition was explored systematically in tree seedlings by Ingestad (1981), who developed ratios of foliar nutrient concentrations in relation to nitrogen that are widely applicable to trees. He has pointed out that:

> "the traditional experimental technique has produced some serious artifacts which are caused by a lacking correspondence between nutrient additions, carried out as concentration treatments, and the actual and exponentially increasing amounts of nutrients required by the plants. The internal nutrient status is therefore not maintained at stable state. The result is the classical nutrition/growth relationships: optimum curves between nutrient status and yield and Mitscherlich-curves between nutrient addition and yield indicating 'diminishing return' of nutrient addition. When nutrients are added as a relative addition rate, nutrient status and relative growth rate remain in a steady

state and strong linear relationships are found between relative addition rate and nutrient status, and between nutrient status and relative growth rate, which relationships are fundamentally different from the classical ones. As a consequence, growth rate per unit of nitrogen (N productivity) increases or is constant with increasing nitrogen addition or nitrogen status. Furthermore, maximum relative growth rate is sharply definable at saturation of the internal nutrient status beyond which a further increase of the relative addition rate has no growth stimulating effect."

Application of these universally balanced nutrient ratios to solutions for seedling nutrition in container stock has spectacularly improved stock production.

Application of the same concept in the forest is more recent. The idea is to provide optimum nutrition in the forest. The SWECON project in mid-Sweden Scots pine has done this. Tables 2 and 3 show some data from Axelsson (1981) for a forest irrigated with balanced nutrient solutions. Not only is the very large growth increase of interest in a harsh boreal climate, but also the apparent increase in efficiency due to much less production of fine roots.

Table 2--Annual biomass (DW) production in a 20-year-old Scots pine stand at Ivantjarnsheden, mid-Sweden percentage production, (Axelsson 1981)

Treatment[1/]	Needles	Branches current	Branches old	Stems	Stumps	Roots coarse (>2mm)	Roots fine (<2mm)	Total
	(%)							
0	19.1	2.6	8.7	12.7	2.7	13.2	17.5	100.0
I	18.0	5.4	14.3	15.0	4.0	8.0	35.0	100.0
F	24.4	6.7	13.9	15.1	3.3	19.1	41.0	100.0
IF	23.3	10.3	19.5	17.3	4.7	10.3	14.5	100.0

1/ 0 = control, I = daily irrigation, F = solid fertilization once a year, IF = daily liquid fertilization. Treatment period: late summer 1974-1979.

Table 3--Biomass (DW.) and relative productivity in a 20-year-old Scots pine stand at Ivantjarnsheden, mid-Sweden. All figures refer to 1979 (Axelsson 1981)

Treatment[1/]	Needle biomass	Stem biomass	Total annual prod. per needle biomass	Total annual prod. per N added	Needle prod. per N added	Stem prod. per N added	Stem biomass per needle biomass	Stem prod. per needle biomass
	(kg/ha)	(kg/ha)	(kg/kg)	(kg/kg N)	(kg/kg N)	(kg/kg N)	(kg/kg)	(kg/kg)
0	2310 (100%)	3036 (100%)	1.93 (100%)	--	--	--	1.31	0.25
I	2542 (110%)	3582 (118%)	2.06 (107%)	--	--	--	1.41	0.31
F	6408 (277%)	6867 (226%)	1.63 (84%)	21.8	5.3	3.3	1.07	0.25
IF	6777 (293%)	8835 (291%)	1.86 (96%)	14.5	3.4	2.5	1.30	0.32

1/ 0 = control, I = daily irrigation, F = solid fertilization once a year until 1979 480 kg N, 120 kg K, and 60 kg P per ha, IF = daily liquid fertilization, until 1979 870 kg N per ha, all other essential nutrients in proportion to N.

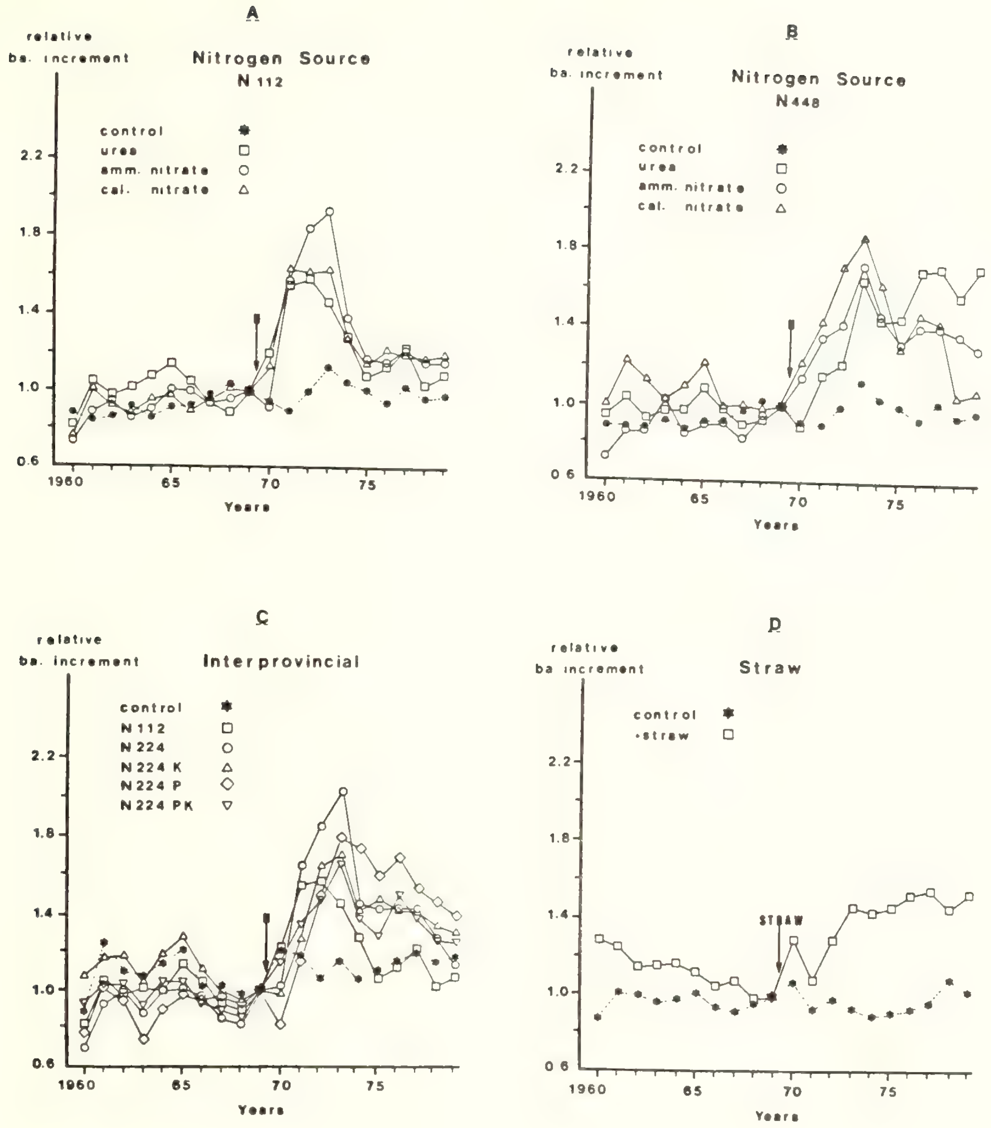

Figure 3.--The effects of single fertilizer additions, and a treatment of straw added on snow to smother ground vegetation, on the annual basal area increment in a 40-year-old Pinus banksiana Lamb. stand.

The nutritional constraint is obviously very strong. There is a strong body of evidence to demonstrate that availability of N is the primary limiting nutritional factor in northern temperate glaciated soils in the USSR (Shumakov 1981), Scandinavia (Tamm 1980), North America, and also in the non-glaciated Cascade Range and Coast Ranges in Washington and Oregon (Regional Forest Nutrition Research Project 1979). There have been many fertilizer trials to show how growth rates can be temporarily "bumped" upward by N additions. Such bumps are associated with increases in foliar N concentrations. Sustained increases in foliar percent of N can be maintained by repeated N additions. The search for the optimum percent of N and the associated sustained maximum growth rate can be done via optimum nutrition trials that empirically test various N regimes by repeated fertilization over 10-year periods. Figures 3 and 4 illustrate the responses from single and repeated N additions in Pinus banksiana.

The optimum foliar percent of N in the forest stand (e.g., 1.4 percent N for pine) is lower than that found in juvenile nursery stock. This empirical approach, based on repeated N additions, is necessary because we still lack

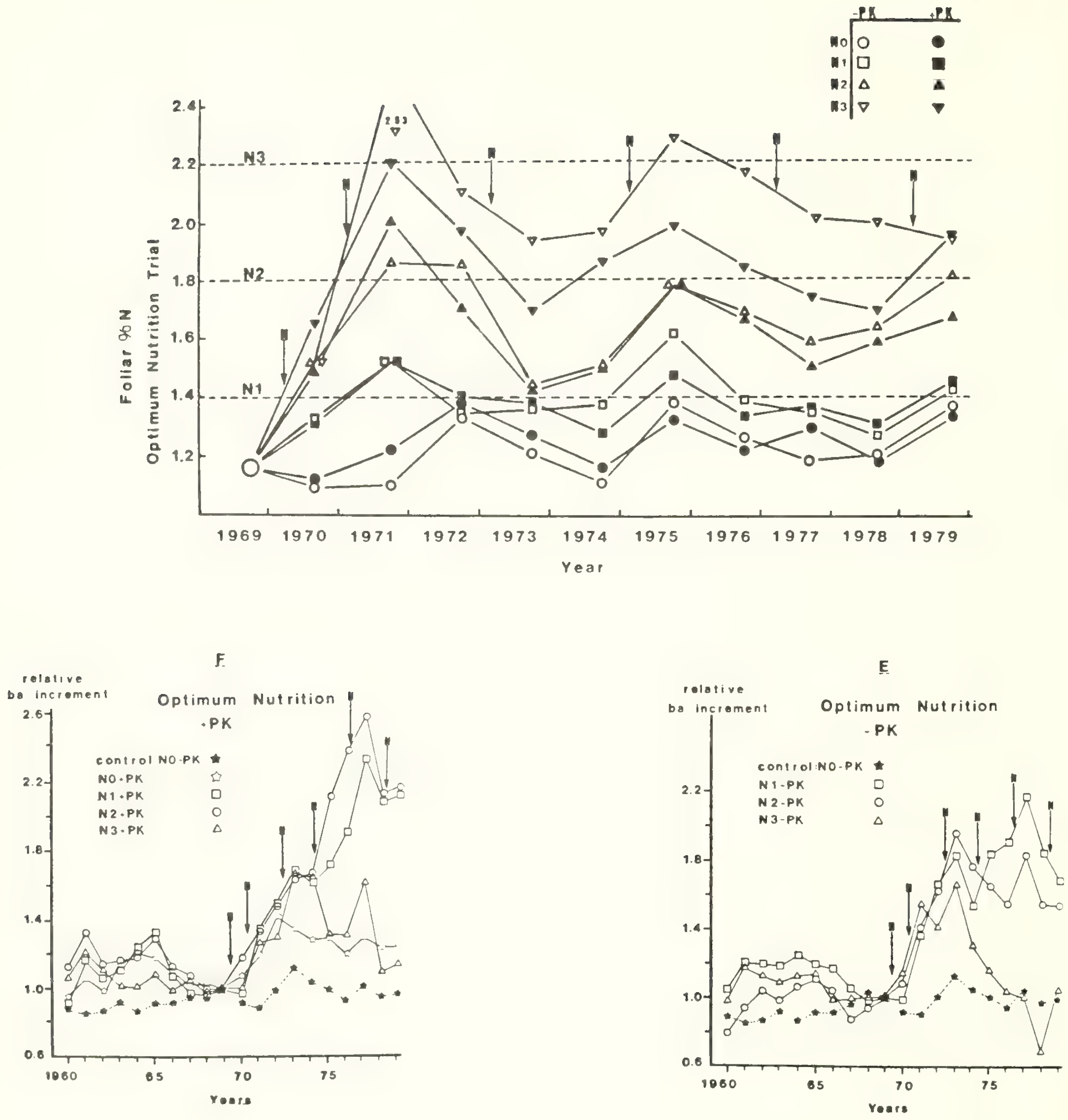

Figure 4.--The effects of repeated fertilization on foliar percent N and annual basal area increment in a 40-year-old Pinus banksiana Lamb. stand.

those elusive measures of soil or stand N status that will predict response to N addition. The "black box" of soil N transformations, so intensively studied, still remains mysterious. Simulators do make prediction based on pool sizes and transfers, but our understanding of the chemical and microbial processes is weak.

N mineralization as an index has some predictive value, but it is a crude index as it only appears to work in some situations. We can screen stands in 1 year for potential responses and formally test them over 5 to 10 years for actual response.

How far can we "push" the stands by improved N nutrition? Some experimental data suggests we can push them far indeed. Temporary increases of +20 to 30 percent in current increment on medium sites are common in trials with single applications of nitrogen, responses of +60 percent have been found. Optimum fertilization may push this response much higher. Fertilizer efficiencies range from 8 to 30 kg of N required for each cubic meter of fertilizer-produced wood (Jonsson 1977, Harrington and Miller 1979, Morrison 1982, Regional Forest Nutrition Project 1979). The temporary "bumps" in growth can in theory be smoothed out. Even when fertilization stops, the buildup of N in the system results in growth increases: for how long isn't known.

The secret in improvement of N supply is in providing small and sustained steady increases in mineral-N, either by N mineralization, N addition, or N fixation. The amounts and timing must match tree requirements. The additions of sewage sludge by Dale Cole and coworkers appear to do this. Cole (1981) reported, for young Douglas-fir, a 400 kg N/ha application of sludge resulted in 50 percent uptake by the trees, producing 10 t/ha of forest biomass indicative of the high uptake potential of the trees. The paradox of N supply is the presence of large organic-N pools, but low mineralization rates (Swank and Waide 1980). Attempts to unlock, accelerate, or prime this organic pool have not been very successful; liming is clearly not the answer.

The body of humus N-availability theory goes back almost 100 years; its organic chemistry is worse than that of lignin as far as understanding is concerned. The whole process of N-availability is microbially mediated and really not well understood. The controls on the box--temperature, moisture, C:N ratios, etc.--have been examined in detail. It may be much more complex than we thought. The Gadgil and Gadgil effect, which suggests mycorrhizal inhibition of litter decomposition, further complicates the picture (Berg and Lindberg 1980). Even the length and magnitude of the flush of N or other nutrient availability following clearcutting, the "assart effect" of Tamm, is little understood; the Hubbard-Brook experience with NO_3-N awoke all as to its importance.

Bosatta et al. (1980) have described the NINIT model for N transformations in a Scots pine forest and made some important points about its validation (see fig. 5): (1) a major problem is that the actual measurements of seasonal variation in N uptake by root populations of whole forest stands are not feasible with present-day techniques; (2) this makes evaluation of plant nutrient recycling in the field very difficult; and (3) testing appears to be the only way to reach a safe conclusion about such models.

If understanding of N availability in forests is the key to unlocking the "black box", which allows prediction of ultimate productivity of many North American forests, then there is a long way to go. The Swedes, using 87 plots from 51 trials in pine and spruce, have developed a function for the prediction of fertilizer response after different fertilizer intervals. This function only explains 50 percent of the observed variation; the standard deviation was 3.8 m^3/ha for years of increment (Ericksson and Jansson 1980, Moller 1980).

We are bound by technique, we know what to study, we can simulate it, but we cannot do it. This is a strong case for properly supported basic scientific studies.

Meanwhile, we must rely on empirical testing. More optimum nutrition trials, involving formal

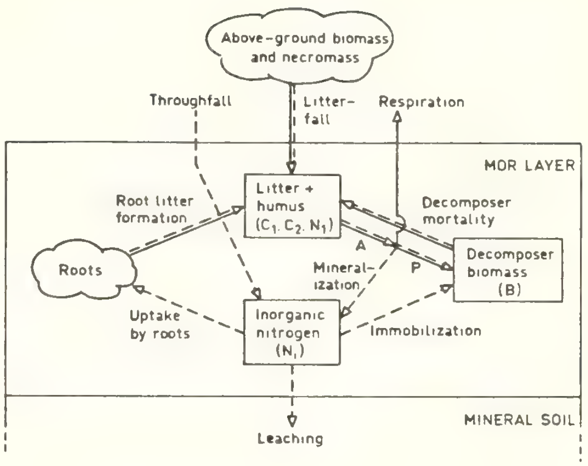

Figure 5.--The structure of the NINIT model, represented by some components and processes of carbon (solid line) and nitrogen (broken line). A = assimilation (decomposition), P = production (incorporation into decomposer biomass). (From Bosatta, Bringmark and Staef, 1980.)

approaches to refertilization, are required for the major types of forests.

A note of caution about maximizing productivity. High physiological "fitness" associated with high growth is also usually associated with resistance to insect and disease attack. No real problems seem to have emerged, but root rot fungi may be a problem (Laiho 1979). Also, nagging questions remain about stability and reproducibility of such forests. Central Europe is receiving a widespread continuous and elevated (to 10-25 kg N/ha input of N because of industrialization and acid rain. Spruce and fir forests appear to be under stress (Tamm 1979). Is the stress due to the N or heavy metals or other pollutants?

Some ideas about stability and diversity relationships have undergone change, and the natural evidence for North American forests does not support the idea that planted forests or forests resulting from human disturbances are functionally less stable than virgin forests (Botkin 1980). Increasing productivity will change the site class, however, and create a new type of ecosystem. New plants will invade and so may new fauna. The caution really addresses whether or not these association changes are desirable in terms of land use.

Increased browsing damage on trees, noted in heavily fertilized forests growing at the physiological optimum, may not represent the ecological optimum desired.

Miller (1981) in reviewing the guiding concepts in forest fertilization has pointed out that:

1. Fertilizers are applied to the trees and not to the site because the annual nitrogen uptake of control and N-fertilized trees required to complete growth is the same.

2. Modest N applications have little effect on long-term site improvement. Even though litter from fertilized trees releases N more rapidly, the quantities are small in relation to the original soil N reserves.

3. Massive N applications, as in sewage sludge 4 000 kg/ha, could be expected to change long-term site productivity.

4. Response can be thought of as reductions in rotation length.

5. There are three distinct nutritional stages in the life of a stand (fig. 6).

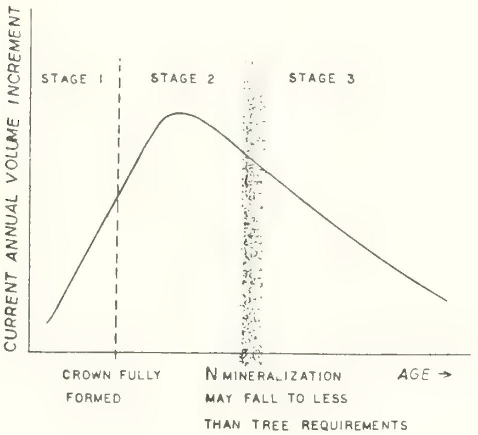

Figure 6.--Nutritional stages in the life of a stand (from Miller 1981).

Stage I occurs prior to full crown development when trees are very dependent on soil supplies and may thus be responsive. Stage II is after closure when trees depend on recycling, with tree immobilization at a low rate. Stage III is after a buildup of humus and immobilization of N when N mineralization may be insufficient and the trees are responsive to N additions.

This view of fertilization points out that relief of soil concentration deficiencies before stand closure can greatly influence subsequent stand growth. This is particularly valid for afforestation on degraded sites, as in Britain. For North America we are generally growing trees for sites that have grown trees for 10,000 years, since the last ice age or longer; the native fertility is usually intact. Young stands, promptly established on these sites and with their low-nutrient demand, may not be responsive to N additions. This may be particularly true if rapid N mineralization is occurring on rich sites.

The opportunities for achieving ultimate productivity in young stands in North America may be limited to Stage II when canopies close and N deficiencies express themselves. Exceptions to these cases are poor sites or sites where N reserves have been reduced; e.g., slashburning on poor sites or perhaps sites invaded by ericaceous vegetation or other brush species that have "captured" the assart effect. In this case, usually on poorer sites of which there are plenty, the Stage I trees offer the best opportunities for diagnosis. While foliar analysis may indicate "low" levels, other site factors (moisture, plant competition, soil depth) may be limiting. The ultimate proof still lies in empirically testing the response.

Opportunities during Stages II and III for ultimate productivity depend on the N mineralization rates. This is where our simulation models may be very helpful in identifying the opportunities. Unfortunately as noted before, it is difficult to measure them. Again, we must fall back on empirical trials.

CONCLUSIONS

All these concepts and problems about pushing the forest to its ultimate productivity by nutritional manipulation suggest:

1. That the potential for growth is much greater than is expressed naturally, and that this potential is often constrained by the annual supply of mineral N. The potential may be as high as 50 $m^3.ha^{-1}.yr^{-1}$ for stemwood under optimum growing conditions, and in the absence of physical damage, for tolerant conifers.

2. By careful manipulation of the quantities and timing of N additions, growth rates can be greatly accelerated and sustained on a wide range of sites; i.e., to make up for the deficiencies of site-dependent endogenous N mineralization rate.

3. Great difficulty is experienced in measuring the key processes and it is still necessary to proceed empirically. Some new techniques are needed to measure N availability and uptake.

4. We also cannot site-specifically measure the magnitude of moisture and plant competition constraints to maximum productivity for our natural forests.

5. In the best of possible worlds, a systematic program of field testing plus an enhanced program of basic scientific investigations on these constraints should produce some scientific breakthroughs or prediction of productivity.

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THE PRODUCTIVITY RESILIENCE OF FOREST SOILS

G. O. Klock

ABSTRACT: A concept is presented by which the sensitivity of soils to silvicultural activities can be described. Soils can be classified into one of five productivity resilience zones based on the intrinsic properties of the soil. The value and utility of such a classification in helping forest land managers to recognize soil factors limiting productivity and the sensitivity of soil productivity to major forest management activities is discussed.

INTRODUCTION

Extensive forestry research has been directed towards identifying and evaluating site factors that affect or control the productivity of forest ecosystems. In a recent literature review on the impacts of soil management on forest site productivity (Klock and Grier[1/]), the need for a descriptive term with an intensity scale to describe the relative sensitivity of a forest soil to disturbance became apparent. The term is needed to improve site survey descriptions, to compare soils research results among numerous study sites, and to improve technology transfer from research to management. The objective of this presentation is to present a concept by which the sensitivity of soils to silvicultural activities can be described.

Klock and Grier[1/] pointed out that the extrinsic factors, such as climate and geology, that affect site productivity can rarely be influenced or modified by management in temperate forest ecosystems. The intrinsic soil factors of soil moisture, aeration, and nutrient availability can, however, be modified by forest management activities to influence net primary production in nearly all forest ecosystems. Whether the modification is significant enough to affect current and/or long-term future productivity is highly dependent upon (1) the type and magnitude of the activity, (2) the time of the activity both seasonally and the stage of stand development, and (3) the productivity resilience or sensitivity of the soils being affected.

At the time this research was done, G. O. KLOCK was principal soil scientist with the USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Wenatchee, Washington. Presently he is soil and water scientist, G. O. Klock and Associates, Wenatchee, Washington.

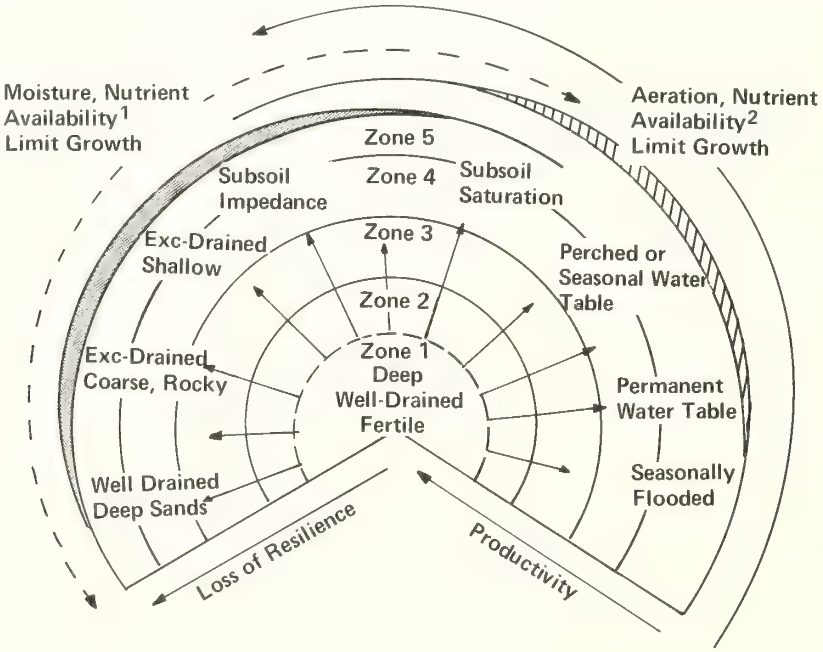
[1/]Klock, G. O. and C. C. Grier. Forest Site Productivity II. The impacts of soil management. Manuscript in preparation. G. O. Klock and Associates, Wenatchee, Washington.

Soil productivity resilience is a term that has not been previously introduced into the science of forest soils. In recent years ecologists have referred to the resilience of natural ecosystems; the degree, manner, and rate of restoration of initial structure and function in an ecosystem after disturbance (Holling 1973, Westman 1978). Resilience as an ecological characteristic reflects ultimately the nature and complexity of many processes within an ecosystem. Westman (1978) pointed out that if researchers "begin to publish information on resilience in standardized ways for particular ecosystems being analyzed, we may at a future date be able to draw some generalization about ecosystem resilience that will enable us to quantify the degree of 'irreversibility of commitment' of ecological resources more effectively." Because soils are a major component of all forest ecosystems, any evaluation of the effects of forest soil management on site productivity must be based on a study of soil characteristics controlling soil productivity resilience. As forest management can have both positive and negative impacts on productivity, evaluation of soil productivity resilience will assist in quantifying both the degree of "opportunity for" and the "irreversibility of" commitment of ecological resources.

Although much literature has been published on the direct impacts of forest management activities on forest ecosystems and stand development dynamics, little is available on the resilience of forest soils to management activities. For clarification of definition, productivity resilience of forest soil is the ability of a particular forest soil to resist significant changes in its moisture, aeration, or nutrient availability characteristics that will affect the site's productivity capacity.

Stone (1978) introduced the concept that changes in soil moisture and aeration affect forest productivity. By adding nutrient availability as a factor to Stone's concept of site productivity gradients, the relation of forest soil productivity resilience to management activities can be developed. Figure 1 displays the full spectrum of intrinsic soil factors of moisture, aeration, and nutrient availability regimes in such a way that one can observe their range, regions of growth limitations, and possible modification by forest management activities.

The great arc displayed in figure 1 embraces all possible combinations of forest soil types. Forest soils approaching the ideal in physical and chemical characteristics and having a high degree of productivity resilience are placed in a group near the center of the figure. Soils within this group, collectively designated as resilience zone 1, can withstand a wide range of forest activities with greater limits of stress before the activity impairs or alters site productivity. Along the periphery of the arc in figure 1 are soils that are characterized by features that are extreme departures from properties of those soils in zone 1. Since soil aeration



[1]Lack of mineral retention sites as well as minimum soil solution retention, subject to leaching losses.

[2]Creates soil reducing condition making some nutrients rather unavailable while others in quantities possibly toxic to forest vegetation.

Figure 1.--A spectrum of soil moisture, soil aeration, nutrient availability and site productivity gradients "Ideal" soil characteristics for maximum site productivity prevail at the center. Most forest soils fall along radial transitions, soil productivity resilience zones 1-5, towards various extremes at the rim. Severity of soil productivity resilience factors varies around the circumference as well as radially.

and plant nutrient availability are frequently related to soil moisture regimes, extreme departures from the ideal are designated by common soil moisture descriptive terms; but there is space for other descriptive terms if needed. These extremes are arranged around the circumference of the arc to indicate magnitude of annual growth stresses, but the soils themselves do not necessarily intergrade smoothly nor are all equally unproductive. Generally unproductive soils with a low level of productivity resilience are usually grouped around the periphery, or resilience zone 5. Sites on soils in zone 5 can easily be altered, resulting in changes in site productivity. The level of resilience may even be low enough to limit or restrict some management activities. Because limitations on the intensity of growth increase from the center outward, and soil resilience decreases along the same vector, the majority of forest soils fall somewhere between the ideal center and the extreme at the periphery as indicated in zones 2 through 4. These zones of resilience also identify opportunities where site productivity can be enhanced or reduction prevented by management options.

Integrating the soil intrinsic factors into gradients of resilience and productivity allows for the influence of extrinsic factors of site productivity wherever they are significant. Describing a soil unit by its dominant physical and chemical properties that characterize its limitations can therefore establish its region or zone of resilience under a given set of extrinsic factors. The potential impact of a given forest management prescription on the soil-related factors affecting net primary production can then be defined. At present, available information only generally indicates the sensitivity or resilience of the soil to a potential impact. With further research, units of scale may be attached to forest soil resilience zones (if necessary, with repetitive degrees of confidence) to predict the impacts of forest management activities on forest productivity in the future.

Table 1 is recommended as a preliminary guideline to determine the level of soil intrinsic factor limitations that places a particular soil unit in a productivity resilience zone. Resilience zone categories can be attached to many presently named soils on mapping units using data from this table.

INTRINSIC SOIL FACTORS AND FOREST MANAGEMENT ACTIVITIES

Extensive silvicultural management practices are carried out in many temperate forest ecosystems. In most cases these silvicultural activities can be grouped into three categories: (1) harvest operations, (2) site preparation, and (3) stand improvements. Each category may or may not have a positive or negative influence on the soil-related factors affecting forest vegetation productivity. The effect often depends on the choice of methods used in each activity (Aber

Table 1--Intrinsic soil factor limitations creating zones of forest soil resilience

Soil resilience zone	Limitations[1/]
1	None
2	Minor nutrient availability
3	Marginal soil water availability Marginal nutrient availability Restricted soil aeration 1. Porosity
4	Serious soil water availability Serious nutrient availability Serious soil aeration 1. Moisture content 2. Porosity
5	Severe soil water availability Severe nutrient availability 1. Deficiency 2. Toxicity Poor aeration 1. Moisture content 2. Porosity

[1/]Each soil resilience zone is identified by one or more soil factor limitations.

et al. 1978). If the activities do influence productivity, the magnitude of the impact is controlled by the productivity resilience of the individual soil or soils affected by the activity.

Harvest operations include the activities of road construction, tree cutting, and yarding; and site preparation entails residue treatments, scarification, drainage, and planting. Stand improvement management covers a wide range of activities, but our discussion will be limited to thinning, drainage, prescribed fire, fertilization, vegetation management (particularly to enhance biologic nitrogen-fixing species), and insect and disease control.

Soils that are classified in productivity resilience zone 1 have no specific intrinsic factor limiting forest management activities such as harvest, site preparation, and stand improvement. This does not, however, preclude the need for good soil stewardship. Soils categorized in resilience zone 1 will erode and compact, and can be depleted of essential nutrients under negligent forest management practices. Opportunities often exist for improving productivity on these soils through stand management practices of thinning and fertilization.

Soils categorized in resilience zone 2 have potential net primary production levels that may

be limited by availability of nutrients--most often nitrogen. Normal timber harvest practices are, again, not expected to have a serious impact on the soil intrinsic factors influencing productivity. Nutrient cycling studies indicate that normal stem harvest removes or causes nutrient losses from the forest ecosystem at rates about equal to nutrient inputs (Stark 1979, Wells and Jorgensen 1979). Harvesting on short rotations and biomass harvesting on soils in resilience zone 2 may, however, place demands upon the soil that exceed the natural nutrient-supplying capacity of the ecosystem (White 1974). The quantitative aspects of the biological, chemical, and physical processes in the soil are insufficiently known to predict the long-term effects of intensive harvest on soil nutrient availability and consequent forest productivity (Jurgenson et al. 1979). Residue treatments following harvest may approach the same demand on site nutrients as intensive biomass harvesting. Thus, a hazard exists on zone 2 soils of decreasing nutrient availability by improper forest residue treatments.

Thinning can be a positive management activity on zone 2 soils if precautionary steps are taken to return the fine organic materials to the soil surface. Returning the fine, nutrient rich organic material to the soil provides the opportunity to concentrate the nutrients on fewer stems, thus increasing possible growth in the remaining stems. It should be noted that thinning most likely will not increase the total productivity on the site, but often puts the growth on fewer stems which results in higher quality stems within a shorter rotation period.

Much has been published on the effects of fire on soils, whether it be for residue treatment in site preparation, fuel hazard reduction, or timber stand improvements (Adams, 1980, Boyer and Dell 1980, DeByle 1981, Downer and Harter 1979, Harvey et al. 1979, Klock and Grier 1981, Kozlowski and Ahlgren 1974, Wells et al. 1978). In general, the effects of fire on nutrient availability have the greatest impact on site nitrogen and sulfur as these key macronutrients may be volatilized and lost from the site. Other nutrients, with the possible exclusion of phosphorus, may be converted to a more soluble form that is subject to loss by leaching from the site. Phosphorus is a rather immobile nutrient and is generally not exported from a forest site by burning. Impacts on nutrient availability would not be expected from prescribed fire on resilience zone 2 soils if there were no significant reduction in the forest floor duff layer. Suggestions are made by Shearer (1974) and Sandburg (1980) to protect the duff layer during the use of prescribed fire.

Much has been written about forest fertilization and its effect on net primary production and mineral cycling (Albrektson et al. 1977). The intent here is not to predict the effects of fertilization on productivity. Fertilization as a forest stand improvement activity used to replace possible nutrients removed during harvest (Adams 1978) is generally quite beneficial in increasing the rate or helping maintain productivity on resilience zone 2 soils.

The most serious limitations to harvest activities in resilience zone 3 soils will be the potential for compaction by yarding activities (Cromack et al. 1979, Froehlich 1979, Miles 1978). Soils in this zone are sensitive to vehicle traffic and will compact under certain moisture conditions and repetitive movement such as frequent use of skid trails. Reduction of soil aeration by changes in the volume and distribution of soil pores can be a hazard. Heavy vehicle movement during site preparation and residue treatments may also have similar impacts.

Some soils may be placed in zone 3 because of their limited capacity for soil water retention, whether from shallow soil depth or coarse textures. Forest stands supported by these soils are frequently subjected to drought conditions, particularly if overstocked. Thinning is a very useful management activity not only for increasing nutrient availability as described earlier but also for reducing evapotranspiration demands and providing more soil water to the remaining stems.

Nutrient availability often becomes critical on zone 3 soils, thereby requiring more detailed analyses of the impacts of intensive biomass removal either by harvest activities, residue treatments, or prescribed burns. Nitrogen is most likely the limiting nutrient, and those management activities that may further reduce the availability of nitrogen should be used with care. Fertilization can be useful on zone 3 soils to overcome productivity limitations because of nutrient unavailability. Timber stand improvement activities should include use of nitrogen-fixing shrubs or tree species early in the rotations to supplement site nitrogen at a rate greater than returned to the site by precipitation and atmospheric fallout. Site preparation activities can also decrease nutrient reserves of a forest site as pointed out by Burger and Pritchett (1979). Scarification, which displaces forest floors and surface soil, may therefore reduce productivity on zone 3 soils. Site preparation activities can also improve site productivity on zone 3 soils by improving soil moisture conditions for seedling survival and growth by enhancing rapid root development, reducing runoff, increasing water infiltration, or reducing competition.

Intrinsic soil factor limitations of resilience zone 4 are often severe. Soil water availability is affected by shallow soil depth and coarser textures that lead to potential drought conditions. Zone 4 soils may have a low productivity because of the unavailability of one or more major macronutrients or possible micronutrients. Forest practices that displace or export plant nutrients, such as whole tree harvesting, intensive residue treatments, site preparation scari-

fication, the removal of organic material for insect and disease control, and prescribed fire, should be used with extreme care.

Productive capacity of zone 4 soils may be easily modified by compaction that reduces soil aeration. Even more serious aeration problems may develop because of high soil moisture content or periodic saturation.

Soils grouped in zone 5 have the lowest resilience or highest sensitivity to changes in productivity due to forest management activities. Nearly all forest soil management activities can affect site productivity on zone 5 soils. This effect can be positive as well as negative. In fact, there are many opportunities to enhance productivity on these soils.

Soils with severe saturation problems or that are periodically flooded have poor aeration. Terry and Hughes (1975) pointed out that the removal of excess water from many poorly drained (resilience zone 5) soils is a prerequisite for adequate logging capabilities, for quality site preparation, as well as for acceptable growth rates in established southern pine plantations. Growth rate response to drainage is generally higher in young stands than in those stands that have basically reached maturity under poor soil aeration conditions.

Soils with extremely low soil-water retention capacity, because of either shallow depth or coarse-textured material, often have severe problems of soil-water availability. Frequently a proportion of the soil water available for use is stored in the organic forest floor layer. Harvest, site preparation, and stand improvement practices reducing the forest floor depth may seriously reduce site productivity.

On some zone 5 soils, severe nutrient deficiencies may exist with one or more macronutrients. Possibly the deficiency is so large that fertilization cannot economically correct the problem. In contrast, other zone 5 soils may have adequate plant nutrients, but the chemistry of flooded soils may reduce their availability or provide their availability in a form, or amounts, toxic to forest vegetation (Patrick 1978). These conditions are developed by biological redox processes that occur under anaerobic conditions or poor soil aeration. Some toxic substances that may be important in well-drained soils, such as aluminum in acid upland soils, are of less concern in wet lands. Potential toxicity, therefore, often depends upon soil pH, among other factors.

SUMMARY

Soil productivity resilience must be evaluated when considering the consequences of or predicting the effects of forest soil disturbance by management practices on future site productivity.

To provide a general scale of resilience intensity, five zones from high to low resilience have been established. It was not the intent here to describe all features that categorize a particular soil into a resilience zone nor the consequences of all forest management activities on soils in each resilience zone. Generalizations have been discussed to provide the forest soil scientist and forest land manager with guidelines to recognize soil factors limiting forest vegetative productivity and the sensitivity levels of soil productivity to major forest management activities.

The discussions presented in this paper are based on interpretation and not demonstrated scientific fact. Continuing research is necessary to give better definition to the concept of soil productivity resilience and the limitations of soils that place them within a particular zone.

The earliest possible use, however, of the concept of soil productivity resilience in evaluations of forest soil site will markedly improve the opportunity to compare forestry research results and assist in extending these results to management applications.

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SITE INDEX RESEARCH IN THE WESTERN HEMLOCK-SITKA SPRUCE FOREST TYPE OF COASTAL ALASKA

Wilbur A. Farr and A. S. Harris

ABSTRACT: This paper reviews site-index research in the western hemlock (Tsuga heterophylla (Raf.) Sarg.)-Sitka spruce (Picea sitchensis Bong.) Carr.) forest type, with emphasis on Alaska. New site-index and height-growth curves have been prepared for hemlock and spruce at low elevations in southeast Alaska. Comparison throughout the range of spruce showed that site-index (50 years) decreases northward at the rate of about 0.8 m per degree of latitude from Lincoln county Oregon to the Gulf of Alaska. Site-index studies are continuing at upper elevations and westward along the Alaskan coast, and soil-site relationships are being investigated.

INTRODUCTION

For the past several years we have been investigating site productivity of the western hemlock-Sitka spruce forest type in Alaska. At the same time, estimates of mean site for geographical areas throughout the type have also been compared to better understand factors that control site productivity or anomalous situations of interest to forest managers in Alaska and elsewhere.

The method of study has been to develop new height growth and site index curves for western hemlock and Sitka spruce in Alaska, compare the growth of these two species on similar sites, compare their growth form with similar curves developed in other areas of the forest type, and attempt to relate site index to variables such as soil type, latitude, elevation, and temperature during the growing season.

Western hemlock-Sitka spruce forests occupy a narrow strip along the coast extending about 2900 km from near Coos Bay, Oregon, to Prince William Sound, Alaska (fig. 1). Both species thrive in the humid, mild climate of the coast where frequent drizzle and summer fog provide well-distributed moisture throughout the growing season.

The hemlock-spruce type is especially well defined in Alaska where it occupies the mainland and coastal islands seaward from the Coast Range. Further south, the type is less well defined, grading into hemlock and Douglas-fir forests a few kilometers inland. The type is generally considered to include coastal stands capable of growing commercially valuable Sitka spruce as a component.

In Alaska, Sitka spruce extends further westward beyond the range of western hemlock, to the Kodiak-Afognak Island group, where its range is continuing to expand to the west. In British Columbia and the conterminous United States, western hemlock extends eastward beyond the range of Sitka spruce to about 820 km inland in western Montana. Spruce, however, is not found far inland where the more continental climatic conditions of summer drought prevail. Lack of a pronounced summer drought is an important feature of these coastal forests and probably allows temperature to play a more prominent role in growth than is the case in many drier locations where interaction with soil moisture can be presumed to have a more dramatic effect on growth.

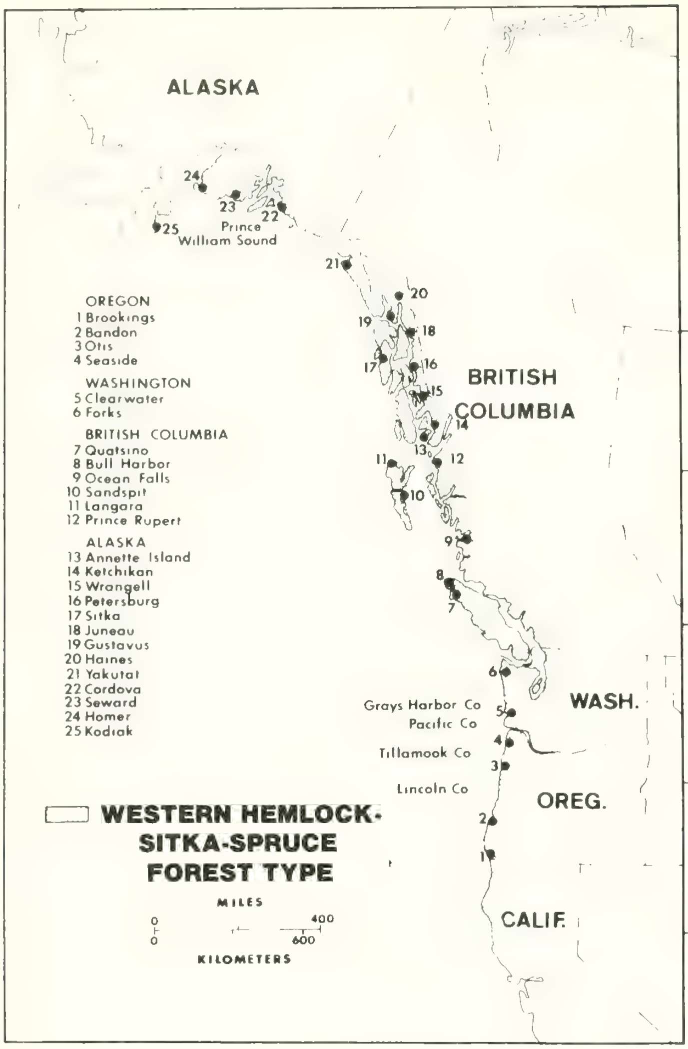

Figure 1.--Approximate range of the western hemlock-Sitka spruce type where mixtures of western hemlock and Sitka spruce occur in commerical stands.

CHANGES IN SITE INDEX

Western hemlock and Sitka spruce grow best near sea level along the coast with site index generally decreasing northward. Although this decrease in site index with latitude is evident from growth and yield studies (Barnes 1962, Meyer 1937, Taylor 1934), we did not analyze it until recently (Farr and Harris 1979).

Many environmental factors contribute to site differences in the hemlock-spruce forest type including heat available for tree growth and soil development, soil parent material, nutrient status, drainage, precipitation, cloudiness, and length of day. We attempted to determine if these factors could be integrated into simple, meaningful relationships between site index and some measure of temperature or latitude.

We used weather summaries of the United States and Canada (Canada Atmospheric Environmental Service 1950-74, U.S. Weather Bureau 1950-1974) and a computer program described by Bakersville and Emin (1969) to compute total annual degree days[1] above various threshold temperatures for a 25-year period for 25 coastal stations (table 1). Mean monthly temperatures were also computed for the same period, but they did not vary appreciably: They ranged from about 15°C along the coast of Washington and Oregon to about 11°C at Prince William Sound, Alaska. The growing season, however, is much longer in the southern part of the range than in the north, suggesting that some other measure should be used to take the longer growing season into account. We finally used cumulative growing degree days above 5°C as a measure of solar input during the growing season because correlations with site were much higher than with other measures of cumulative degree days or summer temperatures. We arbitrarily divided the coast into several geographic areas and calculated a mean site index for each area.

Relationships between mean number of annual degree days and latitude for the period 1950-74 were linear and highly correlated ($P \leq 1$ percent). Of several threshold temperatures tested, 5°C provided the best correlation (fig. 2). Site index of Sitka spruce was also highly correlated with latitude (fig. 3). Yakutat, Prince William Sound, and Kodiak were significant outliers and were not used when the coefficients of the regression line were calculated. The relationship between site index and degree days above 5°C (fig. 4) was also highly significant ($P \leq 1$ percent). Yakutat, Prince William Sound, and Kodiak were again significant outliers (Daniel and Wood 1971), and were not used in the regression.

In our previous work (Farr and Harris 1979), we used provisional site index curves (index age 100 years) for Sitka spruce, based on average height of dominant and codominant spruce and total age, to estimate site index of each of several hundred field plots collected over several decades throughout the hemlock-spruce type.

Since then, Farr[2] has developed separate height growth and site index curves for western hemlock and Sitka spruce in Alaska with an index age of 50 years, based on the average height of the 100 trees of largest diameter per hectare (40 per acre) and breast-high age. These curves are based on a larger sample of trees mostly from areas previously clearcut, and they better describe growth relationships at early stand ages. They are also based on a 50-year, breast-high index age, and are therefore more directly comparable to newer curves developed in the Pacific Northwest.

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[1] One degree day was accumulated for each 1°C rise in temperature above the daily mean when the daily mean temperature was above the minimum threshold of 5°C.

[2] Farr, W. A. Site index and height growth curves for even-aged stands of western hemlock and Sitka spruce in southeast Alaska (manuscript in preparation).

Table 1--Mean number of growing degree days per year above various base temperatures, plus or minus one standard error (+SE), for the period 1950-74

Station name	Latitude (N.)	Mean number of degree days above [a]			
		0°C	5°C	15.6°C	21.1°C
OREGON:					
1 Brookings	42°03'	4,286±34	2,511±31	233± 8	41±3
2 Brandon	43°07'	3,846±64	2,155±47	123±13	7±2
3 Otis	45°02'	3,785±38	2,131±33	231±11	34±3
4 Seaside	45°59'	3,966±36	2,264±32	193± 8	23±2
WASHINGTON:					
5 Clearwater	47°35'	3,562±37	1,963±31	266±10	38±3
6 Forks	47°57'	3,517±37	1,942±30	257±12	56±5
BRITISH COLUMBIA:					
7 Quatsino	50°32'	3,252±44	1,697±34	156±12	20±3
8 Bull Harbor	50°40'	3,029±43	1,434±32	27± 2	1±0
9 Ocean Falls	52°50'	3,127±51	1,676±38	188±14	28±5
10 Sandspit	53°15'	2,943±38	1,455±29	20± 4	0
11 Langara	54°15'	2,750±44	1,204±29	11± 2	0
12 Prince Rupert	54°20'	2,728±45	1,294±31	43± 5	2±1
ALASKA:					
13 Annette Island	55°02'	2,837±54	1,408±39	98± 8	13±2
14 Ketchikan	55°21'	2,911±48	1,472±33	121± 7	16±2
15 Wrangell	56°28'	2,391±48	1,143±33	61± 7	3±1
16 Petersburg	56°49'	2,281±33	1,080±21	54± 4	3±1
17 Sitka	57°03'	2,611±37	1,221±24	38± 3	2±1
18 Juneau	58°22'	2,135±28	1,014±19	71± 5	9±1
19 Gustavus	58°25'	2,146±42	994±29	47± 4	4±1
20 Haines	59°13'	2,263±32	1,159±22	91± 6	12±1
21 Yakutat	59°31'	1,868±31	819±23	19± 2	2±1
22 Cordova	60°30'	1,893±37	851±22	34± 3	3±1
23 Seward	60°07'	2,062±38	989±25	74±28	5±1
24 Homer	59°38'	1,712±27	754±16	15± 2	1±0
25 Kodiak	57°48'	2,002±41	861±24	33± 4	3±1

[a] 0°C (32°F); 5°C (41°F); 15.6°C (60°F); 21.1°C (70°F).

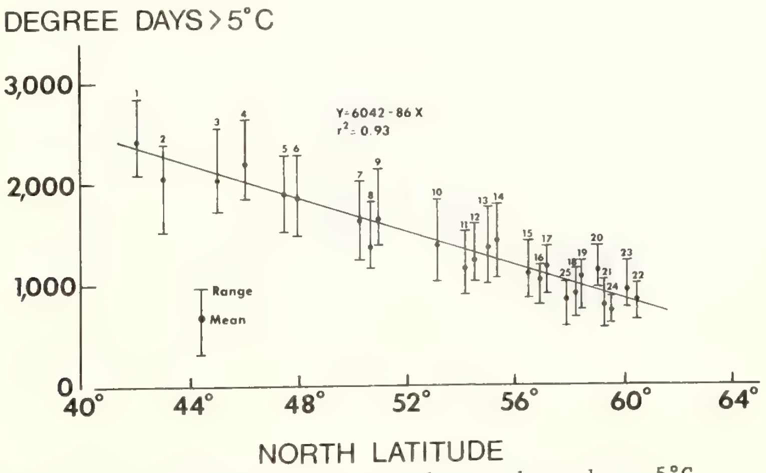

Figure 2.--Relationship between degree days above 5°C and latitude for 25 stations along the north Pacific coast. (See fig. 1 for station names.)

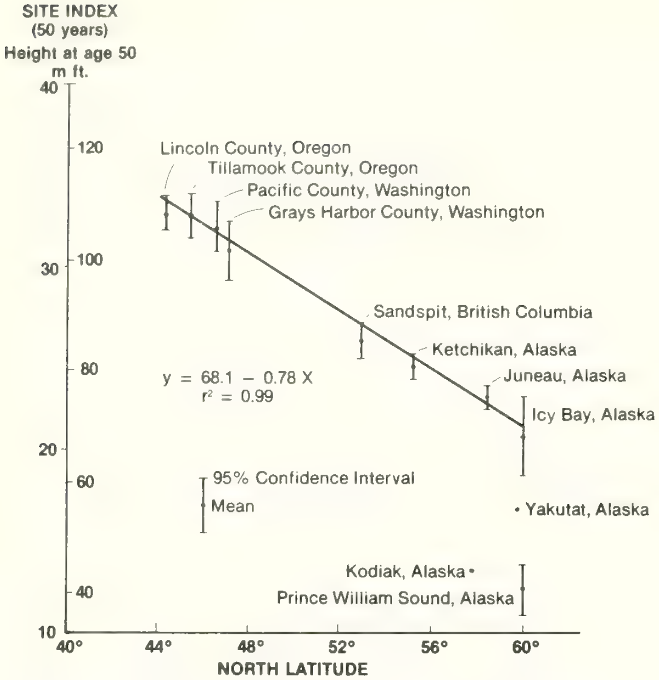

Figure 3.--Relationship between site index of Sitka spruce and latitude along the north Pacific coast. Yakutat, Prince William Sound, and Kodiak were significant outliers and were not included in the regression.

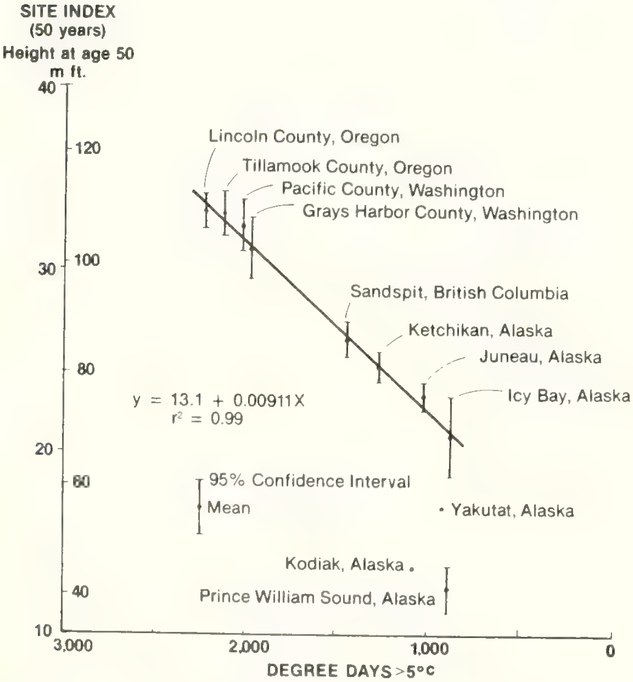

Figure 4.--Relationship between site index of Sitka spruce and degree days greater than 5°C for areas along the north Pacific coast. Yakutat, Prince William Sound, and Kodiak were not included in the regression.

To adjust the original estimates based on an index age of 100 years, we reduced total age by 7 years to approximate breast-high age. The new site curves were then used to estimate site at breast-high age 50, given height at total age 100 years. Some degree of error is no doubt present when making adjustments of this type, but we believe the degree of precision to be adequate for our comparison.

As expected, adoption of a 50-year index age did not affect the straight-line relationship previously obtained between site index and latitude (see fig. 3). Site index (50 years) decreases northward at the rate of about 0.8 m per degree of latitude. As before, average site proved to be lower than predicted at the northwest end of the range, again emphasizing the importance of environmental factors other than temperature during the growing season, and the need for additional site data from this area.

One additional set of data,[3] obtained in 1982 from the portion of the type along the Gulf of Alaska near Icy Bay (latitude 60°N), was included in figure 3. Mean site index based on 20 plots was within 1 m of the predicted average for this latitude.

Little research has been done on soils near Icy Bay. Soils there, however, are derived from sandstones and siltstones, tend to be relatively fine textured, and are more typical of soils found further south. This new data tends to substantiate the relationship between latitude and site index northwestward to latitude 60°N, and further points to youthful soils as an explanation for the unexpectedly low site productivity in the area of Yakutat and much of Prince William Sound.

ESTIMATES OF SITE INDEX

Hemlock and spruce usually grow in mixed stands in coastal Alaska, although pure stands of spruce do occur on highly disturbed sites and in valley bottoms. Pure, or nearly pure, stands of hemlock often become established on poor sites or where abundant advanced regeneration is present at the time the overstory is removed or destroyed.

Hemlock is more shade tolerant than spruce, and in most old-growth stands there is some advanced hemlock regeneration in the understory. When the overstory is removed, advanced regeneration responds to improved light conditions and forms a part of the new stand. In our site work, we have found that breast-high age of hemlock in even-age stands averages about 5 years older than breast-high age of spruce. Seldom is breast-high age of both species the same. The shape of the site curves for the two species also differs, especially for the lower site classes beyond age 50 years. It is important therefore, to assess site index of each species separately if precise estimates of site index are desired.

[3] Data obtained in cooperation with Alaska State Department of Natural Resources. On file at Forestry Sciences Laboratory, Juneau.

We have also found that site index of Sitka spruce in southeast Alaska is usually higher than for western hemlock, especially on higher sites (fig. 5). Meyer (1937) showed that stands having greater percentages of spruce generally have greater basal area, greater average diameters, and greater volume than stands with high percentages of hemlock on similar sites. In general, this means that to maximize volume production, land managers will want to favor spruce, especially on the higher sites.

COMPARISON OF SITE CURVES FOR WESTERN HEMLOCK

Site index curves for combined hemlock and spruce in southeast Alaska were first published by Taylor (1934). About the same time, Meyer began to compile yield data for hemlock and spruce from the entire north Pacific coast (Meyer 1937). Meyer used 300 of Taylor's plots from southeast Alaska, 64 plots from British Columbia, and 294 plots from Washington and Oregon. His proportional site index curves did not differ appreciably from those prepared by Taylor. Later, Barnes (1962), using Meyer's data base, excluded the spruce site trees and all plots that were less than 40 percent stocked (by basal area) with hemlock, and developed site index curves and yield tables for western hemlock along the coast. The site curves of Taylor, Meyer, and Barnes were all proportional in form, indexed at age 100 years, and based on the average height of dominant and codominant trees and total age at the time of measurement.

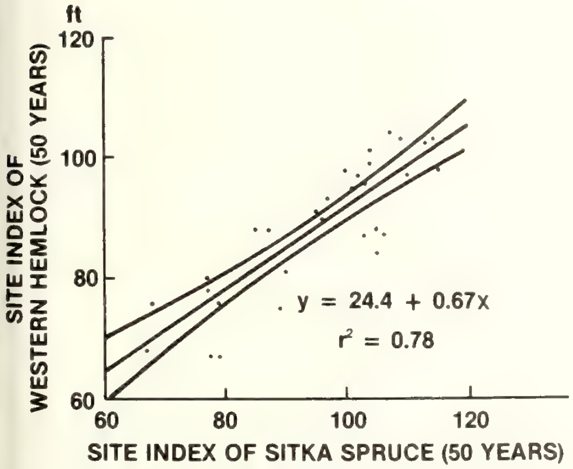

Figure 5.--Relationship between site index (50 years) of western hemlock and Sitka spruce in southeast Alaska showing the regression line and 95-percent confidence interval.

In more recent years, Wiley (1978) prepared new site index curves for western hemlock in the Pacific Northwest, representing a range in site conditions for stands near the Pacific Coast of Washington and Oregon and inland in the Cascade Range. Samples from British Columbia as far north as the Queen Charlotte Islands were also included in the analysis. Wiley's curves are polymorphic in form and based on the average height of the 10 trees of greatest diameter in a group of 50 adjacent individuals, and on breast-high age at the time of measurement.

Wiley showed that a combined equation using all coastal, inland, and British Columbia data was superior to separate equations. A statistically significant bias was found, however, when the equation was applied to stands in British Columbia over 50 years of age. After 50 years, height growth of dominant hemlock in British Columbia slowed so that in later years hemlock was shorter in British Columbia than on comparable sites in the Pacific Northwest. Wiley (1978) prepared an adjustment equation for older stands but cautioned that it was based on only 41 observations from 10 plots and was nonsignificant, raising the question of whether the observations truly represent the height growth of British Columbia stands over 50 years old.

New site index and height growth equations (see footnote 2) will soon be available for hemlock and spruce in southeast Alaska showing growth differences between the species. They are based on average height of the 100 largest diameter trees per hectare (40 per acre) and breast-high age at time of measurement. Since Wiley's work with western hemlock in the Pacific Northwest and British Columbia suggested a possible lowering of height growth with latitude after age 50, we compared his curves with the new curves for western hemlock in southeast Alaska.

Both sets of curves were developed using different procedures. Wiley used Prodan's equation ($H = A^2/[a + bA + cA^2] + 4.5$) to develop a height growth equation as a function of site and age. He then transformed the final height equation to solve for site as a function of height and age. Farr used a procedure similar to that used by Dahms (1975) and Cochran (1979a, 1979b) to develop separate height growth and site index equations. The site index equation was developed directly as a function of height and age.

Two comparisons are made, the first (fig. 6) showing Wiley's and Farr's height curves, and the second (fig. 7) showing Wiley's height curves and Farr's site index curves. In figure 7, total height is plotted as the dependent variable instead of site index for ease of comparison with figure 6, and because site curves have traditionally been shown in this form.

Comparison of the height curves derived from data from opposite ends of the range of western hemlock tends to support Wiley's conclusion, and a provisional conclusion by Harris and Farr (1974, p. 75), that after age 50 years, height growth of dominant hemlock in northern stands is less than on comparative sites in the Pacific Northwest, especially for the higher sites. The differences shown in figure 6 appear, however, to be about half as great as those shown by Wiley (1978, p. 14). For sites below average, there may be no difference or the trend may be reversed.

For purposes of site index prediction, it is more appropriate to compare Wiley's height curves for the Pacific Northwest with Farr's site index curves for southeast Alaska (fig. 7). Beyond age 50 years, the two sets of curves are similar with maximum site differences of up to about 2 m over the range of height and age classes. Differences

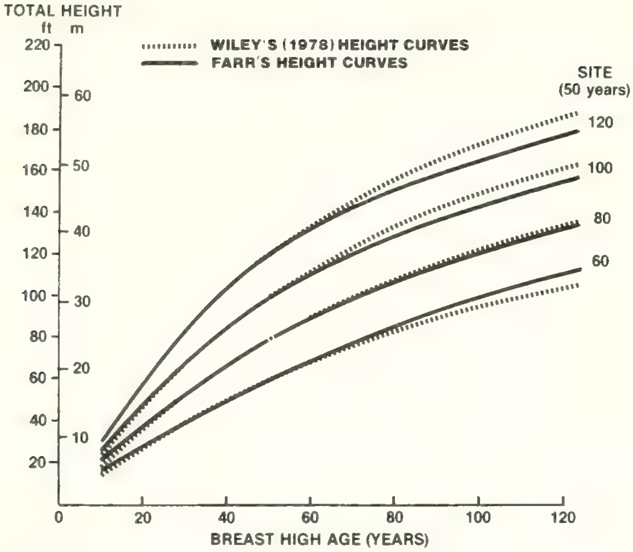

Figure 6.--Comparison of Farr's (unpublished) height growth curves for western hemlock in southeast Alaska with Wiley's (1978) height growth curves for western hemlock in the Pacific Northwest. Measurements are in feet (0.305 m).

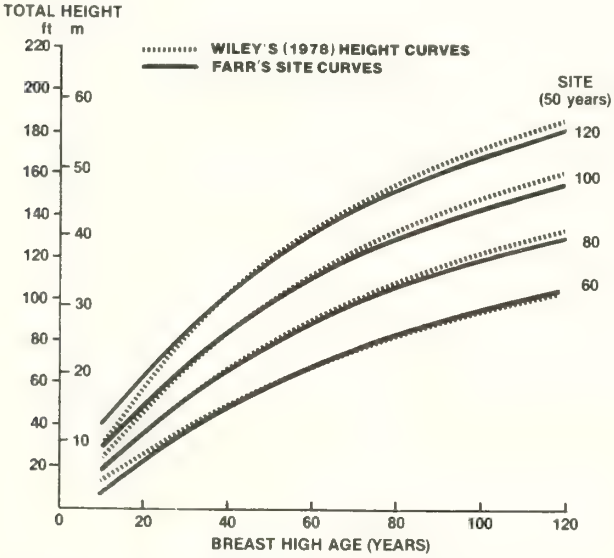

Figure 7.--Comparison of Farr's (unpublished) site index curves for western hemlock in southeast Alaska with Wiley's (1978) height growth curves for western hemlock in the Pacific Northwest. Total height is plotted on the dependent variable instead of site index for east of comparison between figures 6 and 7 and because site curves have traditionally been shown in this form.

below age 50 are due to differences in the way separate height and site curves are constructed. Site index estimation curves will not generally pass through the origin, reflecting the fact that estimates of site index at very young ages are highly uncertain. At these ages, height gives little or no information about site index although the conventional family of site curves passing through the origin falsely implies that it does (Curtis and others 1974, p. 81).

Users of the two sets of curves should be aware that Wiley's entire sample included only 9 stands 100 years or older in age, and Farr's, only 17 stands. These are relatively small samples to precisely characterize curve form at advanced ages, several decades beyond index age 50 years. A much larger sample throughout the type would be needed to determine if a statistical difference actually exists in the form of the curves over the range of the type. We do know from our work in southeast Alaska that soil series or family-specific site curves may some day be required for some major forest soils as growth trends often show marked variation from regional averages.

CURRENT SITE RESEARCH

Site assessment work is continuing in southeast Alaska and in other areas, principally by the USDA Forest Service around Prince William Sound and by the Alaska Department of Natural Resources on State lands near Icy Bay in the Gulf of Alaska and at Haines in cooperation with the Pacific Northwest Forest and Range Experiment Station.

The new curves for southeast Alaska (see footnote 2) were developed from stem analysis data of sample trees, mostly from previously logged areas below 100 m in elevation. Little is known about site productivity at upper elevations, although in recent years an increasing percentage of the harvest has taken place at elevations between 200 m and 500 m. Last year we began site assessment work at upper elevations of four locations. This work will continue for the next several years as stands of logging or fire origin are located.

About 90 percent of the commercial forest land in coastal Alaska is still occupied by old-growth stands of western hemlock and Sitka spruce. There are relatively few older, even-aged stands of logging origin, and they are mostly located at low elevations adjacent to saltwater. Because of the preponderance of old-growth timber in the region and the need to assess future productivity of even-aged stands where the old-growth is harvested, we are investigating the possibility of using relationships between soil and site to predict future site index. Forest Service soil scientists have been gathering information on the chemical and physical properties of soils of all previously established site index plots in coastal Alaska. As these data become available, we will develop predictive relationships to assist land managers in their future planning efforts.

About 8 years ago we started a cooperative study on the effects of stand density on growth and yield of even-aged stands of hemlock and spruce. Since 1974, about 200 plots 0.4 hectare in size have been installed on Federal, State, and private lands in southeast Alaska and more are being added each year. Plots range in age from 10 to 100 years and include sites commonly found on productive forest land. The objectives of this study are to develop a managed-stand simulator and to assess species mixtures and their effects on future yield. The physical and chemical properties of the soils on these plots are also being inventoried to form part of the data base for the analysis of soil-site relationships.

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FACTORS WHICH DETERMINE SITE PRODUCTIVITY IN INTERIOR ALASKA TAIGA ECOSYSTEMS

John Yarie and Keith Van Cleve

ABSTRACT: Relationships of soil and forest floor properties to productivity of black and white spruce (Picea mariana (Mill.) B.S.P. and P. glauca (Moench) Voss) were studied in the Porcupine River Drainage of interior Alaska and compared to an intensively studied area of black spruce near Fairbanks. Results did not indicate that relationships observed in the Fairbanks area hold in the extensive Porcupine unit. The significant relationships of permafrost depth and an expression of soil organic matter quality (C/P ratio) to productivity in the Porcupine River Drainage Unit, however, suggest that site productivity is linked to soil and forest floor temperatures as observed in the Fairbanks study area.

INTRODUCTION

Wise silvicultural decisions are based on a number of considerations. One of the most important is a knowledge of the factors that control site productivity in a particular geographic region. These factors, which tend to be unique to the northern boreal forest, include: large seasonal fluctuations in the length of the day and temperature, a short growing season, low soil temperature and the occurrence of permafrost. Forest floor and mineral soil temperature and moisture, in conjunction with forest floor chemistry (organic matter quality), interact through a series of feedback mechanisms to control organic matter decomposition, nutrient availability, and tree productivity. The black spruce ecosystem is the extreme example of low productivity and nutrient limitation in interior Alaska forests.

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Delineation of these environmental controls and their interactions was the focus of a multidisciplinary study concentrated on black spruce (Picea mariana (Mill.) B.S.P.) ecosystems. This was an intensive study carried out in the vicinity of Fairbanks, Alaska. The central hypothesis of that study was "that ecosystem differences in productivity and degree of nutrient limitation are controlled mainly by soil and forest-floor temperature" (Van Cleve et al. 1983). Based on the hypothesis, a number of critical variables, upon which community relationships depend, are suggested: These are soil temperature, organic matter depth, decomposition rate, fire susceptibility and fire history, nutrient status, primary productivity, soil moisture, successional state, and the environmental factors of aspect, elevation, slope and soil drainage.

To be truely applicable to a regional forestry operation the site factors must also be shown to control site productivity over a large region. Close to the conclusion of the intensive study an opportunity arose to gather evidence in support of the hypothesis over an extensive area of interior Alaska. For 2 years, data was collected from a 3 600 000-hectare inventory unit in northeastern interior Alaska with help and

support from the field crews of the USDA Forest Service, Forestry Sciences Laboratory in Anchorage, Alaska. This paper examines the environmental relationships described in the Fairbanks area on a regional basis. By so doing we should be able to determine the regional applicability of conclusions drawn from the Fairbanks study.

DESCRIPTION OF THE STUDY AREA

Porcupine Unit

The area is 3 600 000 ha in size and is centered on the Porcupine River Drainage of interior Alaska. The area includes four physiographic divisions (Wahrhaftig, 1965). The two major divisions are the Yukon Flats Section and the Porcupine Plateau; the minor divisions include the Ogilvie Mountains and the Old Crow Plain.

The Yukon Flats Section consists of marshy lake-dotted flats ranging in elevation from 91 to 275 m. The northern part of the flats is made up of gently sloping outwash fans of the Sheenjek River or nearly flat floodplains. Rolling silt- and gravel-covered marginal terraces rise above the flats and slope gradually upward to altitudes of about 460 m. Permafrost underlies most of the section except rivers, recently abandoned meander belts, and large thaw lakes.

The Porcupine Plateau is dominated by low ridges having gentle slopes and rounded to flat summits 460 to 762 m above sea level. Valley floors are broad, and valley patterns irregular. The entire section is underlain by continuous permafrost. The remaining two divisions occupy only small areas near the Canadian border and were not described.

The climate is continental subarctic. Temperature extremes vary widely: data from Fort Yukon show a record high of 37.8°C and low of -61.1°C. Annual precipitation is low, averaging less than 25.4 cm a year. The average annual precipitation for Fort Yukon is 15.4 cm (table 1).

The distribution of forest communities described in the Porcupine Unit (Yarie 1983a) follows previously reported relationships for interior Alaska taiga (Viereck 1975, Yarie in press, Van Cleve et al. 1983). A continuum from warm dry sites to cold wet sites appears to exist. Hardwood communities are at the warm end of the continuum, with black spruce communities at the cold wet end. Mixed hardwood-conifer and white spruce communities are found at intermediate positions along the continuum. A more complete description of the communities and vegetation classification can be found in Yarie (1983a).

Because of the extensive nature of the unit, a larger number of communities were encountered and, as a result of the random nature of the sample, not all parts of the hypothesized environmental gradients were equally represented.

A brief description of the Fairbanks study area is included for comparative purposes.

Fairbanks Area

The intensive and semi-intensive sites were located in the Yukon-Tanana uplands (Wahrhaftig 1965) which are characterized by rounded even topped ridges with gentle side slopes. The ridges are 915 to 1 525 m in elevation and rise 450 to 915 m above the adjacent valleys. Valleys are generally flat with alluvium floors and are 0.4 to 0.8 km wide. The entire section is underlain by discontinuous permafrost.

The climate of the Fairbanks study area is also continental subarctic and is very similar to the Porcupine Unit. The Fairbanks area shows a slightly lower summer temperature and higher total precipitation (table 1).

The black spruce ecosystem intensive study site was located about 45 km north of Fairbanks and was representative of a large area of interior Alaska taiga. The dominant vegetation type being Picea mariana feathermoss growing on soils with shallow permafrost (Viereck and Dyrness 1980). Nineteen semi-intensive sites were also selected for study. These sites, all within 50 km of Fairbanks, represent the complete spectrum from the coldest sites to the warmest and driest sites that support tree growth.

The stands in the floodplain represent a typical successional series found along the Tanana River. The series includes two Populus balsamifera/alnus/Equisetum stands, two Picea glauca/feathermoss stands, a mixed Picea glauca-Picea mariana/Sphagnum stand and an open Picea mariana/feathermoss stand. The latter two are typical of older terraces underlain by permafrost. This successional sequence is described in detail by Van Cleve and Viereck (1981).

Table 1--Climate summary for Fairbanks and Fort Yukon (Porcupine Unit)

	Fairbanks	Fort Yukon
Average Minimum Summer Temp (°C)	4	1
Average Maximum Summer Temp (°C)	22	22
Average Minimum Winter Temp (°C)	-30	-34
Average Maximum Winter Temp (°C)	-3	-8
Temperature Extremes (°C)	-52 to 37	-61 to 38
Average Annual Precipitation (mm)	279	178
Average Snowfall (mm)	1778	1143

The upland semi-intensive sites represent a wide variety of environmental conditions. The warmest driest site was a Populus tremuloides/grass/ Artemisia stand on a south-facing cliff above the Tanana River. A Populus tremuloides/Viburnum/ Linnaea borealis stand and two Betula papyrifera/ Alnus/Calamagrostis stands represent the deciduous forest stage following fire in productive permafrost-free upland sites. The final stage was represented by a closed Picea glauca/ feathermoss stand.

The colder upland sites were represented by stands of closed Picea mariana/feathermoss, Picea mariana/feathermoss/Cladonia and an open Picea mariana/Sphagnum stand. The coldest site is an open treeline stand of the Picea mariana-Picea glauca/Betula nana/feathermoss type. Most of these types are underlain by permafrost.

METHODS

Fairbanks Area

The methods used to study the cycling and compartmental distribution of biomass and nutrients can be found in Dyrness and Grigal (1979), Van Cleve et al. (1981), Viereck et al. (1979), and Skre and Oechel (1981). Results of their studies are briefly presented only for comparative purposes.

Porcupine Unit

Field data were collected in conjunction with a renewable resource inventory of the study unit. A stratified double sampling scheme was used to select 520 field plots. Of these, 365 were used in a study of the vegetation and vegetation-environment relationships (Yarie 1983a,b). The remaining plots were not used because they occurred over non-forest lands or water, or in a few cases the vegetation description was incomplete. A vegetation classification was developed (Yarie, 1983a) using an indicator species analysis similar to that of Hill et al. (1975).

We were able to collect organic matter samples from 65 of the 365 vegetation plots. Chemical analysis of these samples follows methods outlined by Van Cleve et al. (1981).

Correlation and regression analysis was run on either the plot data from the subsample of stands with a white or black spruce overstory or an average value calculated from the plot data for each described community. Only plots with an overstory age greater than 50 years were used. This restriction was considered necessary to eliminate the effect of stand age on environmental parameters.

RESULTS AND DISCUSSION

A detailed presentation of the central hypothesis and results of the work carried out in the Fairbanks area can be found in Van Cleve et al. (1983, 1982, 1981), and Dyrness (1982). A brief overview of those results will be presented here so that the validity of the relationships found for the Fairbanks area can be evaluated from data collected in the Porcupine Unit.

Summary of Fairbanks Ecosystem Dynamics

In general, the cold soil temperature results in reduced organic matter decomposition and subsequent accumulation. This accumulation works as a positive feedback and reduces soil temperature even further. Associated with the increasing quantity of organic matter is an increase in moisture of soil and organic horizons and a decrease in pH. These conditions are then favorable for the increased growth and slower decomposition of moss and more conservative nutrient cycling strategies by the vascular plants. These factors result in reduced organic matter quality and a subsequent reduction of organic matter decomposition rates.

Results from the Fairbanks study have shown that black spruce forest floors are thick and contain more biomass when compared to other forest types. These conditions are illustrated by the negative correlation between soil temperature and forest floor depth ($r^2 = -0.71$) across an array of vegetation types (figure 5 in Van Cleve et al. 1981). Also, an increase in average seasonal water content in the forest floor is negatively correlated with soil temperature ($r^2 = -0.75$), with the values for black spruce ranging between 120 to 240. The other forest types are encountered on warmer drier sites.

Chemical characteristics of the forest floor also show substantial ranges among forest types. The nitrogen and lignin concentrations are strongly correlated ($r^2 = 0.69$ and -0.45, respectively) with soil temperature. Black spruce ecosystems were found on the nutritionally poorer sites. The physical and chemical characteristics of the black spruce forest floor are the least favorable to support rapid mineralization of organic matter and the cycling of elements for tree growth.

The net result of this degree of physical and chemical control on forest floor decomposition is the accumulation of a thick slowly decaying organic layer. This results in reduced annual tree production and elemental requirement which is encountered in black spruce.

Comparisons - Fairbanks vs Porcupine Unit

All of the above results were obtained from the intensive and semi-intensive study sites around the Fairbanks area. These sites were specifically chosen to represent the environmental continuum found in the area and thought to exist throughout the Alaska taiga. The Porcupine Unit is part of that taiga and differs in a number of geologic and climatic parameters. The sites studied in the Porcupine Unit were selected at random to fulfill the objectives of a large scale

resource inventory. If the same relationships were found in the Porcupine Unit as in the Fairbanks area, the applicability of the central hypothesis for ecosystem interpretation and silvicultural prescription could therefore be extended to a much broader area of interior Alaska.

The hypothesized processes that control the distribution of biomass (figure 13.4 in Van Cleve and Viereck 1981) can be reorganized and presented to represent their effects on site productivity from the standpoint of tree growth (fig. 1). The one factor that is not included in this presentation is the feedback through litterfall to organic matter quality.

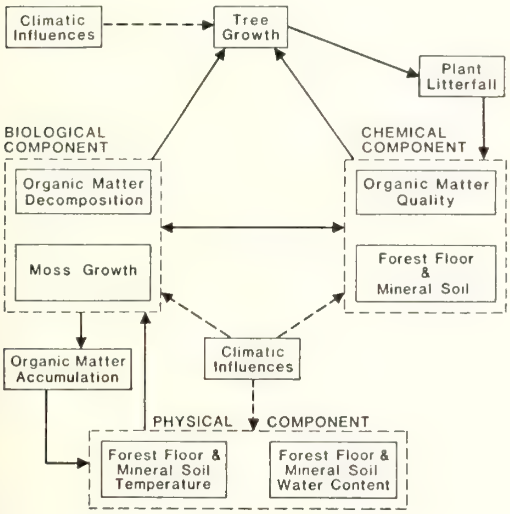

Figure 1. The relationship of factors controlling site quality to tree productivity.

Analysis of the average community data from the Porcupine Unit shows no relationship between organic matter depth and depth to permafrost, or between C/N ratio and tree growth as indicated by the estimated current annual increment divided by stand basal area (CAI/BA). There was no direct measure of moss growth or organic matter decomposition on the Porcupine sample plots. Based on the average community data it is impossible to confirm or deny the applicability of the site controls presented in figure 1.

The lack of strong relationships in the average community data is thought to be a result of the extensive nature of the inventory work, the totally random nature of site selection, and the fact that each site was visited only once during the study. Because each site was visited only once throughout a summer field season, the depths to permafrost tended to be greater in the fall than early summer. There was no way to avoid this phenomenon and it was thought that averaging community values would tend to minimize this problem.

Because it was felt that the relationships depicted in figure 1 are valid for the Porcupine Unit, a subsequent analysis was run using only the mature spruce data set (table 2).

Again, forest floor depth and biomass were not correlated with depth to permafrost. Sample date was only found to be a consideration when looking at black spruce or mixed spruce sites. Correlations for the combined group of spruce plots indicated that there were significant relationships between depth to permafrost and a group of chemical components. Although these relationships were somewhat indirect because there is no direct evidence of a relationship to the biological component of site quality as indicated by figure 1. The path from the physical component to the chemical component goes through and is affected by the biological component (fig. 1).

Tree growth was related to several of the measured chemical components (Table 2). Again, there was no direct measure of organic matter decomposition or moss growth, but an indirect estimate of "k" was available using a relationship between organic matter biomass and k developed for the Fairbanks area ($k = 0.1503$ (KG/m^2 organic matter biomass) -0.8993 $n = 23$, $r^2 = 0.6433$). This estimated value of k was subsequently not found to be correlated to either depth to permafrost or tree growth (CAI/BA).

The site quality flow chart (fig. 1) also suggests various regression analyses that can be applied to the data set. White spruce growth was not found to be related to depth to permafrost using any combination of independent variables (table 3). While the combination of forest floor biomass and the calculated k value did account for a significant amount of the variation in a density independent measure of tree growth (CAI/BA). The same relationship was found for black spruce, although the grams of carbon in the forest floor was also related to black spruce growth. In this instance forest floor carbon content may also represent an indirect measure of forest floor decomposition. There were no significant relationships for the mixed white spruce-black spruce sites. The lack of any relationship for mixed stands is probably due to the small sample size. Also, black spruce growth was probably not related to depth to permafrost because the depth to permafrost was highly correlated to sample date (table 2). We suspect that the growth of white spruce was not related to depth to permafrost because white spruce occurs on sites that exceed some critical threshold for soil temperature. Above this threshold temperature value the feedback between litterfall and organic layer quality may be the overriding site control for tree growth. Soil moisture will then become an important control on sites that reach the hot end of the temperature continuum. The combined data set indicated that both tree growth and depth to permafrost are dependent on the appropriate variables as hypothesized in figure 1 (table 3).

Table 2--Correlation analysis of mature spruce sites sampled in the Porcupine Inventory Unit

Stand type/ variable	Drainage	Depth to perma- frost	pH	Forest floor C/N	%C	%P	gms C	C/P	Sample date
	(r^2)								
White spruce (n = 13)									
Permafrost*[1]				-.533					
CAI/BA[2]									
BA[3]					-.542	-.513			
Black spruce (n = 6)									
Permafrost			-.949						.837
CAI/BA			.603	-.765					
White spruce-Black spruce mix									
Permafrost (n = 5)	.745			-.836					.988
CAI/BA (n = 6)	.755								
Combined group									
Permafrost (n=24)	.536			-.456	-.611			-.661	
CAI/BA (n = 25)	.425	.578		.345	-.653		-.601	-.615	

[1]Depth to permafrost
[2]Stand current annual increment divided by basal area.
[3]Stand basal area

Table 3--Regression coefficients for relationships between measures of the biological, chemical, and physical components of factors controlling site quality for the mature spruce stand types sampled in the Porcupine Inventory Unit.

Stand type	Dependent variable	Independent variables: Forest floor biomass	k[1]	Depth to permafrost	Forest floor carbon	Sample date	n	R^2
		(gms/m^2)		(cm)	(gms)			
White spruce	CAI/BA[2]	-.00775	-1665.8	---	---	---	12	0.519
	Permafrost[3]	---	---	---	---	---		
Black spruce	CAI/BA	.01603	1343.9	---	-0.3729	---	5	0.969
	Permafrost	---	---	---	---	.272	5	0.701
White spruce-Black spruce mix	CAI/BA	---	---	---	---	---		
	Permafrost	---	---	---	.00095	.438	4	0.979
Combined	CAI/BA	---	-420.59	0.1717	-.0069	---	24	0.563
	Permafrost	0.0077	---	---	-.0227	.480	24	0.479

All regressions shown are significant (= 0.05). A dash indicates that the coefficient was not used in the equation.

[1]k was estimated using the following equation k = 0.1503 (kg/m^2 organic matter biomass) - 0.8993
[2]CAI/BA is the stand current annual increment divided by basal area
[3]Depth to permafrost

The regression analysis covers the path starting at organic matter accumulation and progressing to tree growth without considering the chemical components. In general, we find that shallow depths to permafrost are related to high forest floor C/P (r^2 = -.66, fig. 2) and C/N (r^2 = -.45) ratios for the combined spruce sites (fig. 3). The combined effect of soil temperature and one expression of organic matter quality (fig. 3) indicates that both have an important effect on

tree growth, but that reasonable growth can still be obtained on cold sites if the C/P ratio is narrow. This combination of cold sites with low C/P ratios may not be found naturally, but the relationship indicates that regardless of temperature status spruce sites could respond to fertilization.

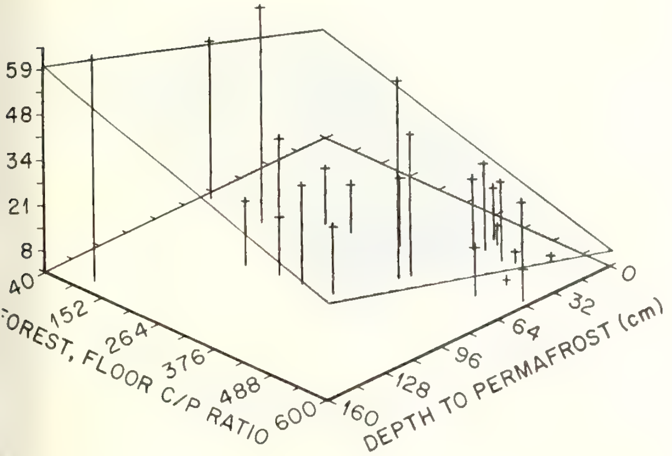

Figure 2. The relationship between depth to permafrost, carbon-phosphorus ratio and a density independent measure of tree growth (CAI/BA). The plotted plane is represented by CAI/BA = 34.81 + 0.15 (depth to permafrost) - 0.05 (C/P ratio). The R^2 for this relationship is 0.44.

CONCLUSIONS

Based on the analysis of data collected from an extensive sample of the Porcupine River Drainage in interior Alaska, we cannot definitely say that site controls suggested for the Fairbanks area are operating in the Porcupine Inventory Unit. But the evidence presented here indicates that the biological, chemical, and physical factors that control site productivity in the Fairbanks area appear to be the same as in the Porcupine Unit. We currently find no reason to suggest that silvicultural practices developed for interior Alaskan forests around the Fairbanks area could not be extended to the large region of interior Alaska north of the Alaska Mountain Range.

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PRODUCTIVITY OF CONIFERS IN WESTERN CANADA BOREAL FORESTS IN RELATION TO SELECTED ENVIRONMENTAL FACTORS

Donald J. Pluth and Ian G. W. Corns

ABSTRACT: The productivity of the conifer-dominated, natural forests within the western Boreal region ranges between 0.7 and 6.4 $m^3\ ha^{-1}yr^{-1}$ in gross mean annual volume increment (70 year) or between 12 and 27 m in site index (70 yr) for jack pine, lodgepole pine, white spruce, black spruce and tamarack. Climatic, topographic and soil moisture regime variables are correlated with forest productivity as revealed through simple and multivariate statistical methods. Stratification of Boreal forest land according to community types provides an estimate of current tree productivity at a precision equal to or better than an estimate associated with soil mapping units. Ideas for improvement in the accuracy and precision of estimates of forest productivity emphasize methods that in principle disclose environmental factor-productivity relationships.

INTRODUCTION

Stratification of forest land into groups distinguished according to tree productivity or prediction of tree growth from a complex of climatic, edaphic and site features have been and continue to be the goals in forest site quality investigations. Carmean (1975) reviewed the rationale for requiring knowledge of forest site quality and comprehensively reviewed the methodology for its estimation. A greater intensity of management of forest land is the underlying impetus for determination of productive capacity. Expectations in forest yield and quality, responsiveness to intensive silvicultural practices, species selection for valued products and shorter rotations necessitate an accurate estimation of site quality according to Carmean. His review article provides the conceptual background and terminology for our review of the state-of-the-art in forest site quality estimation for the most prevalent, indigenous coniferous species in Western Canada. We present the actual productivities for coniferous species in unmanaged forests and identify environmental factors associated with the best tree growth. The methods for estimating forest site quality are compared for their apparent accuracy and precision for stratification of forest lands into tree productivity classes.

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DESCRIPTION OF FOREST LANDS

The geographical area referred to as Boreal forests of Western Canada (fig. 1) corresponds with the forest sections Mixedwood (B18a), Lower Foothills (B19a), and Upper Foothills (B19c) of the Boreal forest region, and the East Slope Rockies section (SA1) of the Subalpine forest region (Rowe 1972). Rowe's forest regions essentially represent macroclimatic delineations as inferred from the presence of certain tree species as dominants in climatic climax communities. Forest sections as subdivisions of regions are not defined consistently by specific criteria. The criteria vary according to the forest region. Roughly, limits for the geographical area are latitude 50°N to 59°N and longitude 98°W to 123°W. Ranges and modal values of some natural features characteristic of the forest sections are shown in table 1. The four forest sections occur within the soil moisture subclasses "humid" and "subhumid", defined as water deficits being very slight (2.5 - < 6.4 cm) and significant (6.4 - 12.7 cm), respectively, during the growing season. Soil temperature classes range from moderately cold to cold cryoboreal (Clayton et al. 1977). It is highly probable even though not specifically stated

Table 1--Natural features characteristic of forest sections in the Boreal and Subalpine forest regions[1]

Forest section	Elevation	Tree species[2]			Surficial/bedrock geology	Upland soils
		Predominant	Major	Minor		
	m					
East Slope Rockies	1530-2070	lP	eS, eS-wS hy, sF	wP, aL	Thin glacial drift overlying uplifted Mesozoic shales & sandstone	Variable, shallow to bedrock
Upper Foothills	1220-1530	lP	wS	bS, sF	Glacial drift overlying uplifted & folded Mesozoic and late Paleozoic sedimentary rocks	Eutric Brunisol & Gray Luvisol
Lower Foothills	760-1220	lP	A, bP, wS	bS, bF, sF, T	Glacial drift overlying Mesozoic sedimentary rocks	Gray Luvisol
Mixedwood	200-900	A	bP, wS bF	wB, jP, bS, T	Glacial drift overlying Mesozoic sedimentary rocks	Gray Luvisol

[1]Abstracted from Rowe (1972) and Clayton et al. (1977).

[2]lP - lodgepole pine, A - aspen, eS - Engelmann spruce, eS-wS hy - Engelmann spruce-white spruce hybrid, sF - subalpine fir, wS - white spruce, bP - balsam poplar, bF - balsam fir, wP - whitebark pine, aL - alpine larch, bS - black spruce, T - tamarack, wB - white birch, jP - jack pine.

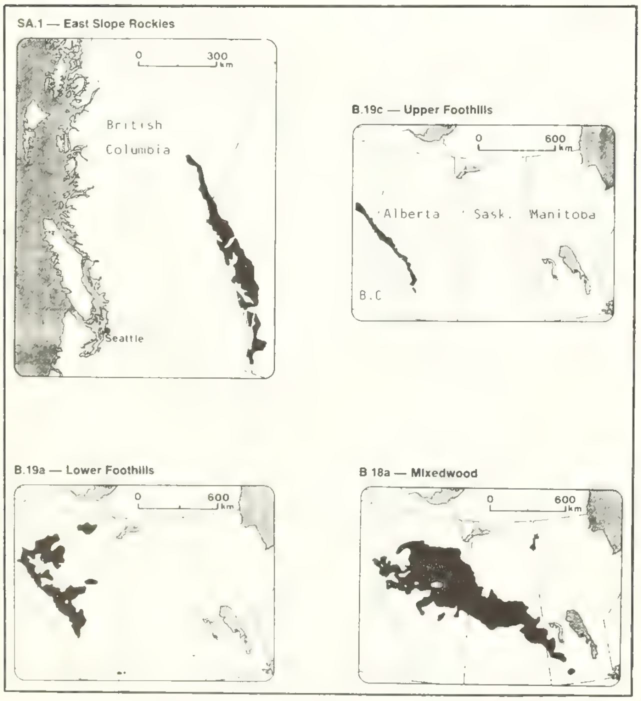

Figure 1.--Some forest sections of the Subalpine (SA) and Boreal (B) forest regions in Western Canada constituting the Boreal forests of Western Canada (from Rowe 1972).

in all of the studies, that the tree components of sampling units for productivity studies on upland soils were natural stands of wildfire origin, and thus even-aged. Those stands with white spruce (*Picea glauca* (Moench) Voss), tamarack (*Larix laricina* (Du Roi) K. Koch), and black spruce (*Picea mariana* (Mill.) BSP) in lowlands would be the most likely to depart from an even-age condition as a result of forest succession and/or of a non-fire origin (black spruce on fens or bogs).

Because estimates of forest productivity in the reviewed studies were from natural stands, actual rather than potential productivity is represented.

FOREST SITE QUALITY STUDIES

In this review we have included quantitative results in contrast with reports with a data base of an observational nature or with a sampling design not amenable to statistical analysis. A minimum level of statistical analysis for review acceptance is a means range test (e.g., Tukey's or Duncan's) or analysis of variance. Those forest site quality studies qualifying on those bases are summarized in table 2. A considerable range in area of a study and in variability in respect to physical site factors affecting productivity is evident.

For a further perspective, the reviewed studies may be categorized according to Carmean's (1975) indirect methods for estimation of site quality. For lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.), all of the site quality studies related a parameter of tree growth to a soil taxonomic class, commonly at the soil series level of generalization. All studies except Duffy (1964) also attempted the plant

Table 2--Forest site quality studies of conifers in the Western Canada Boreal forest region and a description of their samples including sample size

Species	Reference	Area	Sample description (no. plots)
		km^2	
Lodgepole pine *(Pinus contorta* Dougl. var. *Latifolia* Engelm.)	A. Duffy (1964)	3,500	3 soil series (70)
	C. Lesko and Lindsay (1973)	1,200	2 forest types and 12 soil series (ns[1])
	D. Dumanski et al. (1973)	15,000	Community type not determined. Forest inventory data of merchantable volume (60-110 year age class), several soil series and complexes (1116)
	F. Corns (1978)	17,500	8 vegetation types and several soil series (83)
White spruce *(Picea glauca* (Moench) Voss)	B. Duffy (1965)	13,700	Typical species of productivity classes noted, 9 parent materials and 6 soil drainage classes, r-vp (414)
	C. Lesko and Lindsay (1973)		9 forest types and 15 soil series (ns[1])
	E. Kabzems et al. (1976)	76,400	8 ecosystems and 5 soil drainage classes, vr-i (ns[1])
	F. Corns (1978)		3 vegetation types and several soil series (30)
Black spruce *(Picea mariana* (Mill.) B.S.P.)	E. Kabzems et al. (1976)		5 ecosystems and 4 soil drainge classes, mw-vp (ns[1])
	F. Corns (1978)		2 vegetation types and several soil series (15)
Jack pine *(Pinus banksiana* Lamb.)	E. Kabzems et al. (1976)		4 ecosystems and 4 soil drainage classes, vr-i (ns[1])
Tamarack *(Larix laricina* (Du Roi) K. Koch)	E. Kabzems et al. (1976)		3 ecosystems and 1 soil drainage class, vp (ns[1])

[1]ns - sample size not specified for individual tree species. Lesko and Lindsay (1973) had 100 plots ranging over forest types with lodgepole pine, white spruce, and black spruce. Kabzems et al. (1976) had 94 permanent sample plots ranging over ecosystems with white spruce, black spruce, jack pine, and tamarack.

indicator method as an alternative for estimation of tree growth. Soil-site methods (Carmean 1975) were utilized through simple correlation or regression (Lesko and Lindsay 1973, Dumanski et al. 1973). Corns (1978) developed multiple regressions with soil-site and vegetative cover by species as variables in estimation of coefficient parameters of lodgepole pine growth. Except in table 2, where the authors' terms for a vegetation classification are given, the term "community type" is adopted as a single reference to "vegetation type" (Corns 1978), a "forest type" (Lesko and Lindsay 1973), and "ecosystem" (Kabzems et al. 1976).

The studies for estimation of white spruce productivity included similar indirect methods as for lodgepole pine. By stratification according to parent materials and soil drainage classes, Duffy's (1965) method can be considered "quasi-soil survey" in that soil horizon properties were not recognized in sufficient detail to classify his sample sites according to taxonomic unit. Kabzems et al. (1976) stratified by soil drainage class first and then within drainage class by ecosystem. This is a nested arrangement that still may be categorized as a plant indicator method in which sampling units are modified habitat types. Corns' (1978) methodology was multiple: plant indicator, soil survey, and soil-site evaluation (multiple regression).

LODGEPOLE PINE PRODUCTIVITY

Stratification of forest vegetation into community types (a plant indicator method) has provided a

convenient framework for estimating productivity of lodgepole pine (Lesko and Lindsay 1973, Corns 1978). Names of community types recognized the abundance or scarcity of some species by vegetative strata (Lesko and Lindsay 1973) or floristic similarity augmented by edaphic and other environmental factors (Corns 1978).

The mean annual increment (m.a.i.) for lodgepole pine (i.e., the mean annual increment in gross bole volume inside bark averaged over 70 years) ranged from a mean of 4.2 m^2 $ha^{-1}yr^{-1}$ (mean site index (SI) = 19.8 m) for the *P. contorta/Viburnum edule/Rubus pubescens* (PICO/VIED/RUPU) type to 1.3 m^3 $ha^{-1}yr^{-1}$ (mean SI = 11) for the *P. contorta/Vaccinium myrtilloides/Cladonia* spp. (PICO/VAMY/CL) type (table 3). Soil-site conditions associated with this m.a.i. range from lodgepole pine are an occurrence in the Lower Foothills forest section at 880-1040-m elevation, commonly on northerly slopes up to a 30 percent slope gradient, and usually well-drained to imperfectly-drained Gray Luvisols and Eutric Brunisols developed on residual and glacial drift parent materials for the PICO/VIED/RUPU type (fig. 2) of highest productivity. The type PICO/VAMY/CL of lowest productivity is restricted to well-drained, coarse-textured Humo-ferric Podzol and Eutric Brunisol soils developed in fluvial and aeolian parent materials (fig. 2).

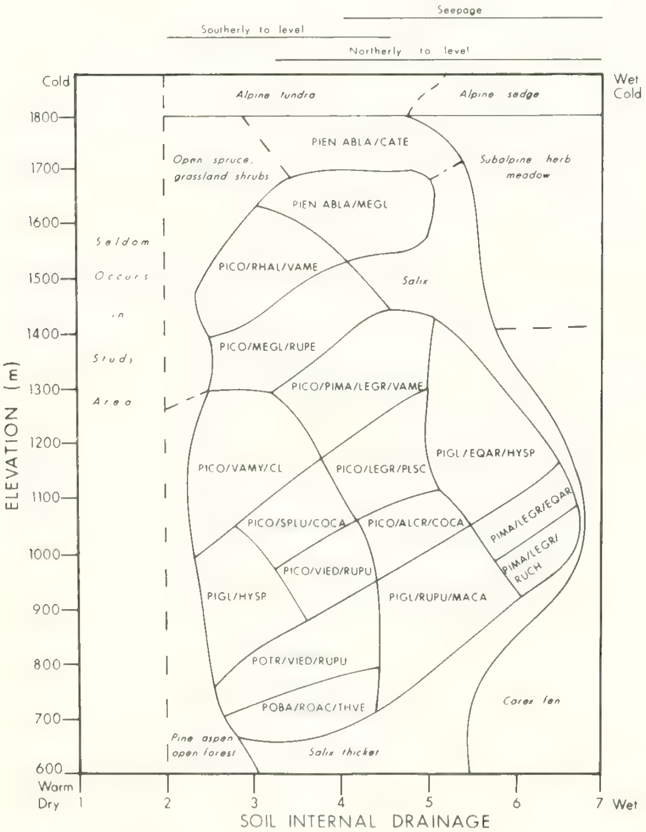

Figure 2--Generalized occurrence of community types of west-central Alberta in an elevation-soil internal drainage class grid (source information from Corns 1978).

Table 4 summarizes productivity-environmental factor relationships for lodgepole pine as disclosed from soil-site studies. Several of these simple statistical relationships suggest either a macroclimate (e.g., length of growing season, precipitation during growing season) or a site moisture regime causal factor. A lodgepole pine productivity that is negatively correlated with elevation (Corns 1978) indicates a macroclimatic influence. Productivity positively correlated with slope angle (Duffy 1964, Corns 1978) and an increase (Corns 1978) or a maximum on north-facing slopes (Dumanski et al. 1973) support a hypothesis of favorable site moisture regime in terms of a tree's water status. That is, short-term productivity depends upon photosynthetic tissue being at a high-water status while stomata are open (Passioura 1982). On the wet or periodically anaerobic end of the scale in site moisture regime, a soil aeration effect on lodgepole pine productivity is inferred from positive correlations with slope angle (Duffy 1964). A periodic annual increment in gross bole volume (p.a.i.) correlation with coarse-textured parent materials (Dumanski et al. 1973) is another possible aeration relationship. More directly, the most favorable site moisture regimes for lodgepole pine are indicated by a site index maximum for moderately well-drained soils (fig. 3). Furthermore, the appearance of the independent variable depth to distinct mottling in a regression for estimation of m.a.i. for lodgepole pine suggests that the most favorable site moisture regime is associated with better drained soils.

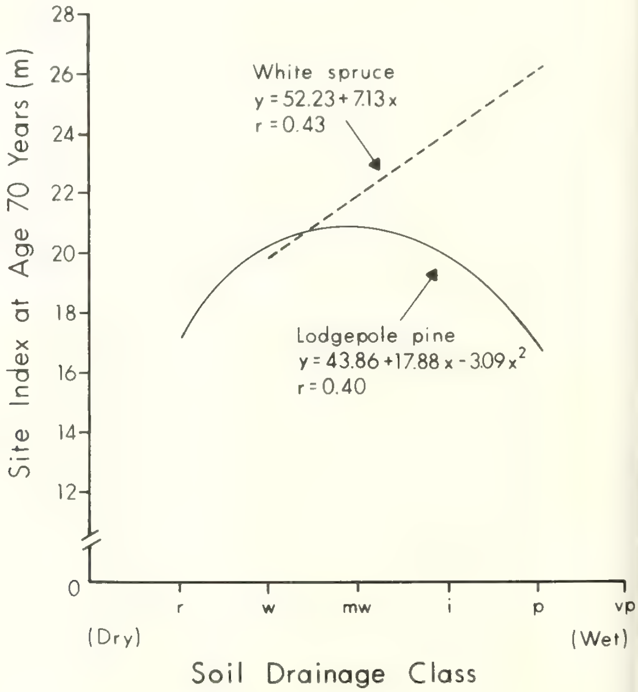

Figure 3--Relationships between the site index of lodgepole pine or white spruce and soil internal drainage class (after Lesko and Lindsay 1973).

Table 3--Some Western Canada Boreal forest types and their associated soil properties and productivity

Type[1] (Reference)	Soil[2]	Drainage[3]	Texture	Productivity m.a.i.[4]	Productivity SI(species)	Age for estimate
				$m^3\ ha^{-1}yr^{-1}$	m	yr
Populus balsamifera/ Rosa acicularis/ Thalictrum venulosum (Corns 1978)	CU.R	w	SL-LS	4.6	18.3 (bP)	70
Populus tremuloides/ Viburnum edule/Rubus pubescens (Corns 1978)	GL.GL, O.GL	w-i	C-HC	4.3 3.0-6.3	19.3 (A)	70
Populus tremuloides/ Aralia nudicaulis/ Linnaea borealis (Kabzems et al. 1976)	Luvisolic	mw	Fine-med.	3.5-3.8	---- (A)	60
Picea glauca/Rubus pubescens-Maianthemum canadense (Corns 1978)	O.GL GL.GL	mw-i	C-HC	4.7 2.9-6.3	18.6 (wS)	70
Picea glauca/Aralia nudicaulis (Lesko and Lindsay 1973)	O.GL, GL.GL	mw-i	C-HC	---	23.8 (wS) 22.9 (lP)	70
Picea glauca/Aralia nudicaulis-Cornus stolonifera (Lesko and Lindsay 1973)	GL.GL	i-p	HC	---	24.1 (wS)	70
Picea glauca-Populus tremuloides/Cornus canadensis (Kabzems et al. 1976)	Luvisolic	w	Fine-med.	3.1	--- (wS)	75
Picea glauca-Populus tremuloides/Cornus canadensis-Rubus pubescens (Kabzems et al. 1976)	Luvisolic	i	Fine	2.4	--- (wS)	75
Picea glauca-Populus tremuloides/Cornus canadensis-Mitella nuda (Kabzems et al. 1976)	Luvisolic	mw	Fine	4.2-4.5	--- (wS)	65
Picea glauca/Picea mariana/Vaccinium myrtilloides (Lesko and Lindsay 1973)	O.GL, GL.GL	i	CL-HC	---	23.2 (wS) 21.3 (lP)	70 70
Pinus contorta-Picea glauca/Arctostaphylos uva-ursi (Lesko and Lindsay 1973)	E.EB, BR.GL	r	LS	---	22.3 (wS) 19.8 (lP)	70 70
Picea mariana-Populus tremuloides/Vaccinium myrtilloides (Lesko and Lindsay 1973)	O.GL	m-w	CL-HC	---	21.3 (lP)	70
Alluvial complex (Lesko and Lindsay 1973)	O.R, GL	m-mw	Med.		21.3 (wS) 20.7 (lP)	70 70
Pinus contorta/ Viburnum edule/Rubus pubescens (Corns 1978)	GL.GL E.EB	i-w	CL-L	4.2 0.7-6.0	19.8 (lP)	70

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Type[1] (Reference)	Soil[2]	Drainage[3]	Texture	Productivity m.a.i.[4]	Productivity SI (species)	Age for estimate
				m^3 $ha^{-1}yr^{-1}$	m	yr
Pinus contorta/Spiraea lucida/Cornus canadensis (Corns 1978)	O.GL, BR.GL	w-mw	CL-L	4.2 3.2-4.6	17.0 (lP)	70
Pinus contorta/Alnus crispa/Cornus canadensis (Corns 1978)	O.GL, BR.GL	mw-i	CL-L	4.0 2.1-5.0	18.2 (lP)	70
Pinus banksiana/Lycopodium annotinum/Pleurozium schreberi (Kabzems et al. 1976)	Luvisolic	mw		2.7-3.2	--- (jP)	65
Pinus contorta/Ledum groenlandicum/Pleurozium schreberi (Corns 1978)	O.GL, BR.GL	mw-i	CL-L	3.8 1.5-5.0	16.3 (lP)	70
Pinus banksiana-Picea mariana/Pleurozium schreberi (Kabzems et al. 1976)	BR.GL	w	CL	1.4-1.7	--- (jP)	75
Picea glauca/Equisetum arvense/Hylocomium splendens (Corns 1978)	O.G, O.LG	p-i	CL-HC	3.7 2.4-6.4	12.5 (wS)	70
Picea glauca/Equisetum arvense (Lesko and Lindsay 1973)	O.GL	vp-p	C	---	24.7 (wS)	70
Picea glauca/Equisetum arvense-Equisetum palustre (Kabzems et al. 1976)	Gleysolic	p	Fine-med.	1.4-1.7	--- (wS)	80
Pinus contorta/Rhododendron albiflorum/Vaccinium membranaceum (Corns 1978)	BR.GL, E.DYB	w-mw	L	3.7 2.1-6.4	--- (lP)	70
Picea glauca/Hylocomium splendens (Corns 1978)	O.R, CU.R	r-w	LS-L	3.6 2.0-4.8	13.2 (wS)	70
Picea glauca/Hylocomium splendens (Lesko and Lindsay 1973)	O.GL	mw	HC	---	22.9 (wS) 22.0 (lP)	70 70
Picea glauca/Abies lasiocarpa/Hylocomium splendens (Lesko and Lindsay 1973)	O.GL	mw-i	CL	---	20.4 (wS)	70
Picea glauca/Lycopodium annotinum (Lesko and Lindsay 1973)	O.GL	mw	CL	---	21.3 (wS) 19.8 (lP)	70 70
Picea glauca/Betula papyrifera/Hylocomium splendens (Lesko and Lindsay 1973)	GL.GL	mw	HC-SiC	---	26.5 (wS)	70

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				$m^3\ ha^{-1}yr^{-1}$	m	yr
Picea glauca/ Pleurozium schreberi (Kabzems et al. 1976)	Luvisolic Luvisolic	w mw	Fine-med. Fine	3.1 4.5	--- (wS) --- (wS)	75 70
Pinus contorta/ Picea mariana/ Ledum groenlandicum/ Vaccinium membranaceum (Corns 1978)	O.GL,	mw	CL-L	3.1 1.3-5.0	14.4 (lP)	70
Populus tremuloides/ Corylus cornuta (Kabzems et al. 1976)	Luvisolic	w	Fine-med.	2.8	--- (wS)	70
Pinus contorta/Menziesia glabella/Rubus pedatus (Corns 1978)	BR.GL	w-mw	L-CL	2.7 1.4-4.3	13.9 (lP)	70
Picea mariana/Pleurozium schreberi-Ptilium crista-castrensis (Kabzems et al. 1976)	Luvisolic	i	Fine-med.	2.1-2.4	--- (bS)	90
Picea mariana/Ledum groenlandicum/ Equisetum arvense (Corns 1978)	T.M, R.G	p	Org-Cl	2.1 1.3-3.2	8.1 (bS)	70
Picea glauca-Populus tremuloides/Corylus cornuta (Kabzems et al. 1976)	Brunisolic	vr-r	CS-Gr	1.7-2.0	--- (wS, A)	80
Picea glauca/ Agropyron subsecundum-Arctostaphylos uva-ursi (Kabzems et al. 1976)	Brunisolic	vr-r	FS	1.0-1.7	--- (wS)	90
Larix laricina/Picea mariana/Ledum groenlandicum/Pleurozium schreberi (Kabzems et al. 1976)	Organic	p	--	1.4	--- (L)	90
Picea engelmannii/ Menziesia glabella/ Rubus pedatus (Corns 1978)	O.GL	mw-i	L-LS	1.4-4.3	17.9 (eS)	70
Pinus contorta/Vaccinium myrtilloides/Cladonia spp. (Corns 1978)	O.HFP	w	LS	1.3	11.9 (lP)	70
Pinus banksiana/ Vaccinium vitis-idaea-Pleurozium schreberi (Kabzems et al. 1976)	BR.GL	w	CL	2.0	--- (jP)	70
Pinus banksiana/ Arctostaphylos uva-ursi-Cladonia spp. (Kabzems et al. 1976	Brunisolic	vr-r	S-LS	0.8-1.0	--- (jP)	80

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Type[1] (Reference)	Soil[2]	Drainage[3]	Texture	Productivity m.a.i.[4]	Productivity SI (species)	Age for estimate
				m^3 $ha^{-1}yr^{-1}$	m	yr
Pinus contorta-Picea mariana/Arctostaphylos uva-ursi (Lesko and Lindsay 1973)	E.EB	r	LS	---	18.0 (1P)	70
Populus tremuloides/Rosa acicularis/Elymus innovatus (Kabzems et al. 1976)	Brunisolic	vr-r	CS-Gr	1.3	--- (A)	80
Larix laricina/Carex aquatilis/Sphagnum spp. (Kabzems et al. 1976)	Organic	vp		0.8	--- (L)	100
Picea mariana/Ledum groenlandicum/Carex spp. (Kabzems et al. 1976)	Organic	vp		0.7-0.8	--- (bS)	130

[1]The community types were distinguished on the basis of vegetational and environmental criteria. The types are ranked within the table according to average productivity. Those types adjacent to the same vertical line are similar floristically and environmentally.

[2]Class abbreviations from Canada Soil Survey Committee, Subcommittee on Soil Classification 1978.

[3]Internal drainage classes: vr - very rapidly, r - rapidly, w - well, mw - moderately well, i - imperfectly, p - poorly, vp - very poorly.

[4]Average (single value) and/or range given for m.a.i.

Very few statistical relationships between a site nutrient regime factor and productivity of a western Boreal conifer have been identified. For lodgepole pine, a p.a.i. optimum from a modal soil pH 5.5 to 6.0 within a specific group of soils (table 4) (Dumanski et al. 1973) was the only such relationship of statistical significance. Some soil-site studies, however, excluded soil fertility variables from consideration on a deliberate but informed basis (Lesko and Lindsay 1973, Corns 1978). The complexity of site nutrient regime and inadequate measurement and interpretation methodology may have been reasons for an exclusion decision.

As an attempt to improve the estimation of productivity, Corns (1978) compared multiple regressions that had both climatic-topographic-edaphic and vegetative cover by species as independent variables. Precision in the estimation of lodgepole pine productivity improved considerably with the inclusion of vegetative cover variables. R^2 values increased from 0.24 to 0.66 for m.a.i. and from 0.49 to 0.71 for site index at 70 years.

A case has been made (Duffy 1962) for the utilization of soil survey information in stratification of forest lands according to productivity. In a soil-site study limited to just three soil series, Duffy (1964) found lodgepole pine height growth to be significantly greater on the two soil series with the finer-textured profiles. Stratification for lodgepole pine productivity, however, was achieved with better success through community type than through soil taxonomic unit or soil map unit (Lesko and Lindsay 1973, Corns 1978). Community types provided a greater number of productivity groups with statistically-different mean productivities. Certainly some relationship exists between community types and soil taxonomic units (commonly soil subgroup or soil series). Lesko and Lindsay (1973) discovered a community type-soil series relationship to be closest only at the extremes in soil internal drainage. Corns (1978) usually found one or two soil subgroups to be most frequently associated with community type (table 3).

We advocate a continued two-way stratification of western Boreal forest land; i.e., according to community type and soil taxonomic unit or soil map unit. This has a potential advantage over a one-way stratification (either by community type or soil unit) in applications in forest land management that are multipurpose. If a single

Table 4--Productivity-environmental factor relationships for lodgepole pine as revealed from soil-site studies in Western Canada Boreal forests[1]

Environmental factor	Simple relationship	Reference
Climatic-Topographic:		
Elevation	Negative correlation with m.a.i. or SI	Corns 1978
Slope angle	Positive correlation with dominant height for soils developed on till	Duffy 1964
	p.a.i. maximum at 15-30 percent	Dumanski et al. 1973
	Positive correlation with m.a.i. or SI	Corns 1978
Aspect	p.a.i. increases on north-facing slopes with sandy and gravelly soils only	Dumanski et al. 1973
	m.a.i. maximum on north to northeast-facing slopes	Corns 1978
Edaphic:		
Soil internal drainage	Curvilinear with SI maximum at moderately well drained	Lesko and Lindsay 1973
	p.a.i. ranked vp < p < i	Dumanski et al. 1973
	Depth to distinct mottling in regression for m.a.i. estimation	Corns 1978
	Basal area highest for rapidly drained sandy outwash	Wali and Krajina 1973
Texture	p.a.i. greater for glaciofluvial sands and gravels than for fine- and medium-textured till and lacustrine parent materials	Dumanski et al. 1973
Stoniness	p.a.i. decreases slightly	Dumanski et al. 1973
pH	p.a.i. optimum for modal soil pH's 5.5-6.0 within Luvisolic soils developed on a calcareous, medium-textured till	Dumanski et al. 1973

[1]Environmental factor compiled only if its simple correlation coefficient or its multiple regression coefficient was significant at the 0.05 level.

objective of land stratification is for productivity of lodgepole pine, then the research evidence in Western Canada Boreal forests favors a stratification based upon community type. A community (vegetation) type defined conceptually as by Corns (1978), (i.e., including some environmental criteria) appears to have greater utility for lodgepole pine productivity than one solely defined by vegetational criteria.

A community (vegetation) type of Corns (1978) differs from the habitat type of Pfister and Arno (1980). The former classifies the current (at sampling) vegetation development and some environmental factors whereas the latter is based on a dynamically stable (climax) state of potential vegetation development.

WHITE SPRUCE PRODUCTIVITY

The m.a.i. for white spruce ranged from a mean of 4.7 $m^3\ ha^{-1}yr^{-1}$ for the *Picea glauca/Rubus pubescens-Maianthemum canadense* type to about 1.4 $m^3\ ha^{-1}yr^{-1}$ for the *Picea glauca/Agropyron subsecundum-Arctostaphylos uva-ursi* type (table 3). The former community type occurs in the Lower Foothills

section at an elevational range of 670-1220 m commonly on north-facing, 0-30 percent slopes with moderately well to imperfectly drained Orthic and Gleyed Gray Luvisols dominant (table 3 and fig. 2). The sites with the lowest m.a.i.'s are found in the Mixedwood section commonly on very rapidly to rapidly drained Brunisolic soils (table 3). The types *Picea glauca/Aralia nudicaulis* and *Picea glauca/Aralia nudicaulis-Cornus stolonifera*, which are similar to the *Picea glauca/Rubus pubescens-Maianthemum canadense* type, had mean site indexes of about 24 m. Very few soil-site factors that are significantly correlated with white spruce productivity have been identified. The m.a.i. was negatively correlated with elevation (Corns 1978). The site index increased linearly along a gradient in soil internal drainage (fig. 3).

As was the case for lodgepole pine, a multiple regression analysis for white spruce productivity, which included vegetative cover by individual species, enhanced predictability (Corns 1978). R^2 values increased from 0.53 to 0.86 for m.a.i., and from 0.58 to 0.91 for SI at 70 years. The multiple regression equation predicting m.a.i. and having an R^2 of 0.86 had nine independent variables with five of them being plant cover variables.

PRODUCTIVITY OF OTHER CONIFERS

Site quality aspects of black spruce, jack pine (*Pinus banksiana* Lamb.) and tamarack (*Larix laricina* (Du Roi) K. Koch) have not been extensively studied in the Western Canada Boreal forest region (table 2). Kabzems et al. (1976) in the Mixedwood section within Saskatchewan estimated productivities for these species according to a soil drainage class by community type stratification (table 3). Productivity of black spruce had a considerable range among community types, from an m.a.i. of about 2.3 $m^3\ ha^{-1}yr^{-1}$ (*Picea mariana/Pleurozium schreberi-Ptilium crista-castrensis* type) to 0.8 $m^3\ ha^{-1}yr^{-1}$ (*Picea mariana/Ledum groenlandicum/Carex* spp. type).

CONCLUSIONS

Stratification of forest lands according to site quality is regarded as a patently essential prerequisite to forest management planning. Forest industry appears to measure forest land productivity by growth and yield of preferred wood products of a defined quality. Any estimation of site quality must therefore be expressed in or closely related to yield of a utilizable wood product and, if possible, to other management concerns.

The number of indigenous tree species present in the Subalpine and Boreal forest regions in Western Canada east of the Rocky Mountains is few. The number of alternative species ecologically adapted to a given site is usually restricted to four or less. For example, the potentially suitable species on a medium-textured, moderately well drained Gray Luvisol site in the Mixedwood section of the Boreal forest region are jack pine, white spruce, black spruce and aspen (*Populus tremuloides* Michx.).

Methods for estimating forest site quality for conifers in Western Canada directly identify or suggest characteristics of site moisture regime and temperature regime as factors controlling productivity. The community type and soil-site evaluation methods have disclosed site factors that can be inferred as direct or indirect controls upon site moisture regime. The method using a soil mapping unit alone seems to provide a stratification by site quality of lesser accuracy than other methods. Perhaps soil mapping units have not been defined to include the appropriate controlling factors of tree productivity or manifestations of these factors. Phasing of a soil taxonomic unit according to mesoclimatic parameters, slope position, aspect, or a parameter related to groundwater flow system may allow improved prediction of forest site quality from a soil mapping unit. Recognition of forest humus form in the soil mapping unit may also aid inferences about site nutrient regime, which is so difficult to quantify for site quality purposes.

A two-way stratification of community type and an appropriately phased soil taxonomic unit is suggested for improvement in the use of landscape units for prediction of site quality. Some site factor-productivity relationships may be inherently expressed by the community type. For example, temperature as a site factor for conifers appears to be neglected in our region, particularly for landscape units near the latitudinal and/or northerly slope extremes for distribution of the species. Community type and edaphic characteristics may be responsive indicators of a temperature factor.

Any substantial increase in the accuracy and precision of an estimate of forest site quality over existing methods probably is dependent upon results from controlled field experiments in our region. Experiments designed to disclose growth and yield-controlling factor relationships are logical as a next step to a functional understanding of factors identified from multivariate statistical analyses common in soil-site evaluations. Presumably, some of the "noise" or "experimental error" sources inherent to current methods of estimation of site quality can be reduced through the experimental approach by manipulation or control of variables such as genotype, stocking level, and spacing on landscape units with some degree of similarity as defined by the current state of knowledge. The extent of valid interpolations and extrapolations for large forest land areas can always be questioned in such an experimental approach. But such results should be applicable to estimates of site quality in artificially regenerated and managed plantations as contrasted with natural conifer stands.

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PRODUCTION IN MIXTURES OF CONIFERS AND RED ALDER: THE IMPORTANCE OF SITE FERTILITY AND STAND AGE

Dan Binkley and Sarah Greene

ABSTRACT: Red alder, a source of biologically-fixed nitrogen, can enhance site fertility and growth of interplanted conifers. On infertile sites, we found mixed alder/conifer stands to have greatly increased rates of ecosystem production; gains in conifer production occurred after age 30 when conifer dominance developed. On fertile sites, mixed stand productivity did not exceed that of pure conifer stands; conifer production was impaired throughout stand development.

INTRODUCTION

Biologic nitrogen (N) fixation offers an alternative to the use of inorganic fertilizers for maintaining or enhancing site fertility. Yet despite considerable discussion and research, N fixation has not been commercially exploited in Pacific Northwest forestry. Recently, researchers have analyzed the biologic and economic potential of using red alder (Alnus rubra Bong.), a N-fixing species, to enhance conifer production (cf. Atkinson et al. 1979, Miller and Murray 1979); but divergent findings from various experimental stands have not allowed uniform endorsement of red alder's potential.

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Tarrant (1961) reported that a 27-year-old mixed red alder/Douglas-fir [Pseudotsuga menzieii (Mirb. Franco] plantation at Wind River, Washington, produced double the total stand volume of an adjacent, pure conifer stand. In a similar study at Cascade Head, Oregon, Bernsten (1961) reported that the yield at age 30 of a naturally establishe red alder/conifer stand was 20% less than that of an adjacent conifer plot where alder had been thinned at age 8. The differences in response between these experimental sites have increased over the past 20 years (Miller and Murray 1978, Greene [1]). The Wind River site is much less fertile than the Cascade Head site, supporting Miller and Murray's (1978) suggestion that the benefits of red alder would probably be greatest c N-deficient sites.

[1] Greene, S. Growth and yield in 50-year-old pure or mixed conifer and red alder stands at Cascade Head, Oregon. Manuscript in preparation.

We hoped consideration of age and site fertility (specifically, N status) would produce a clearer picture of the scope and limits of red alder as a tool for maintaining or enhancing site productivity. We took advantage of the thorough stand records for Cascade Head and calculated estimates of aboveground net primary production for pure conifer, mixed alder/conifer, and pure alder stands through 46 years of stand development. We then combined Cascade Head estimates with ones for three other locations to synthesize a pattern of alder effects in conifer plantations as a function of site fertility and stand age.

SITE DESCRIPTIONS

Each of the four sites discussed here--Cascade Head, Wind River, Skykomish River, Washington and Mount Benson, British Columbia--contains a pure conifer stand paired with an adjacent mixed stand of red alder and conifers. The Cascade Head site also includes a pure alder stand. Douglas-fir is the major conifer in all stands, with a substantial component of Sitka spruce (*Picea sitchensis* (Bong.) Carr.] and western hemlock [*Tsuga heterophylla* (Raf.) Sarg.] occurring only at Cascade Head. Two sites (Wind River and Mount Benson) are infertile Site Class IV, and two (Cascade Head and Skykomish River) are fertile Site Class I or II (table 1).

Cascade Head

Agricultural land, abandoned in 1925, naturally seeded in with mixtures of red alder, Douglas-fir, Sitka spruce, and western hemlock. Thinnings between 1935 and 1937 produced stands of pure conifer, alder/conifer, and pure alder; the pure conifer stand had grown with red alder for about 8 years before thinning. Growth and yield information for these stands (stems > 6 cm diameter at breast height (d.b.h.)) is provided by Bernsten (1961) and Greene[1]; Franklin et al. (1968) evaluated soil properties, and Tarrant et al. (1969) measured aboveground litterfall. The thinning operation that established these plots reduced the density of conifer stems in the pure conifer plot far below that of the mixed alder/conifer plot (table 1). A portion of the response differences between these stands (especially mortality) is therefore attributable to a stocking difference and not to the presence of alder.[2]

Wind River

A 20-m-wide firebreak of red alder was planted within a 2-year-old Douglas-fir plantation. Tarrant (1961) summarized stand growth, yield, and nutrition at age 27, and Miller and Murray (1978) updated the growth and yield information at age 48. Soil properties were described by Tarrant and Miller (1963). The mixed alder/conifer stand had a much higher total stem density (table 1); however, Douglas-fir mortality between ages 27 and 48 was greater without alder (1,000 stems/ha) than with alder (840 stems/ha) (calculated from Tarrant 1961 and Miller and Murray 1978).

Skykomish River

Two-year-old Douglas-fir seedlings were machine planted in a pasture in 1958; and red alder seedlings, naturally established about 1958, were hand cleared from half the plantation between 1962 and 1964. Ecosystem biomass, production, and nutrient content are described by Binkley (1983). The total stocking of these two plots was similar; the addition of alder stems was matched by a proportionate reduction in Douglas-fir stems (table 1). In this situation, the effect of alder on the conifers was due to interspecific competition rather than increased stem density.

Mount Benson

A portion of a 1958 Douglas-fir plantation contained naturally seeded red alder. The pattern of alder establishment did not follow any trend in soil physical properties and was probably restricted by available seed source. Ecosystem descriptions are also reported by Binkley (1983). As at Wind River, the mixed alder/conifer plot at Mount Benson had much higher stocking than the pure conifer plot. The very open canopy of the pure conifer plot indicated considerable underutilization of site resources.

METHODS

Biomass regression equations were applied to stem diameter data from each stand to obtain estimates of aboveground biomass and net primary production. At Cascade Head, 0.2-ha permanent plots were measured 7 times over 50 years; and regression equations (described below) were applied to individual tree tallies and summed for stand totals. For Wind River at age 27, we applied regression equations to stand average d.b.h. and diameter increment (from Tarrant 1961) and multiplied by the number of stems to obtain stand totals; for age 48, we used similar calculations broken down into six average diameter classes provided by Miller and Murray (1978). Estimates for 23-year-old stands at Skykomish River and Mount Benson were calculated by applying regression equations to individual stem tallies (Binkley 1983).

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[2] Binkley, D. The importance of stocking and relative densities in managing mixed stands of Douglas-fir and red alder. Manuscript in review.

Table 1 Site and stand characteristics for four study sites

Characteristic	Cascade Head	Wind River	Skykomish River	Mt. Benson
Location	Central coastal Oregon	Southwestern Washington	Northwestern Washington	Eastern Vancouver Island
Elevation, m	180	600	35	510
Precipitation, cm/yr	250	230	120	200
Douglas-fir site index, m at 50 yr	37	25	45	24
Establishment year (approx.)	1928	1928	1958	1958
Stocking, trees/ha				
Conifer only (age)	1,650 (24)	1,400 (27)	1,860 (23)	650 (23)
Conifer/alder	2,300/1,550	1,100/1,550	1,600/290	540/2,200
Total Soil N, kg/ha				
Without alder	13,000 (to 80 cm	3,200 (to 80 cm	4,650 (to 60 cm	1,560 (to 60 cm
With alder	14,200 in 1966)	4,200 in 1959)	5,570 in 1980)	2,380 in 1980)
Anaerobic available N index, μg/g 0-15 cm				
Without alder	115	25	80	7
With alder	120	100	60	80

All regression equations were obtained from the literature except those for red alder, which were developed on the basis of data from Mount Benson (Binkley 1983). Because all the equations may provide biased estimates, our calculated values can be considered only as "ballpark" figures for stand comparisons. The Douglas-fir and western hemlock equations were taken from Gholz et al. (1979); annual leaf production was assumed to be 20% (Douglas-fir) and 28% (western hemlock) of total leaf biomass (Gholz et al. 1979). Because no equations were available for Sitka spruce, we arbitrarily modified the Douglas-fir equations by subtracting 35% to account for the lower density of spruce boles. We used the Mount Benson red alder equations for all sites. But because both Cascade Head and Wind River alders exceeded the size of the trees used in deriving the Mount Benson equations, we reduced our estimates of alder canopy biomass by 20% for large (stems > 25 cm d.b.h.) trees, judging that the equations overestimated canopy biomass on these two sites by about 20% on the basis of maximum stand canopy biomass for red alder reported by Zavitkovski and Stevens (1972). Stem and branch production at Cascade Head was calculated as the average annual difference between sampling times; at other sites, these estimates were calculated on the basis of 5-year diameter increment and biomass of stems and branches from the 5 years' previous growth as predicted by regression equations. Production estimates for Cascade Head included tree mortality; no mortality estimates were available for the other sites.

RESULTS AND DISCUSSION

Our detailed analysis of the Cascade Head site revealed striking differences among stands. Aboveground tree net primary production (leaf, stem, and branch growth plus mortality) rapidly peaked in the red alder stand, reaching a plateau at about 12 Mg ha^{-1} yr^{-1} between ages 15 and 25 (fig. 1). However, high mortality began at 20 (fig. 2), resulting in a gradual decrease in the rate of tree biomass accumulation (fig. 3). Aboveground net primary production of the mixed alder/conifer and pure conifer stands was similar throughout stand development (fig. 1); however, mortality was much greater in the more densely stocked mixed stand (fig. 2). This difference led to a much greater accumulation of aboveground tree biomass in the pure conifer stand by age 50 (fig. 3). Before age 20, the pure alder stand was more productive and accumulated more tree biomass than either of the stands with conifers. After that time, the pure conifer stand outperformed the mixed stand, which exceeded the pure alder stand.

The patterns in production and tree biomass in the 23-year-old Skykomish River stands were similar to those at Cascade Head at the same age (fig. 4). Production for these fertile sites consistently exceeded the average value reported by Grier (1979) for the Douglas-fir forest zone. Though Sykomish River was more productive than Cascade Head, at both sites red alder failed to increase total stand production or biomass. The proportional decrease in conifer production was greater at Cascade Head, where alder stocking was much higher.

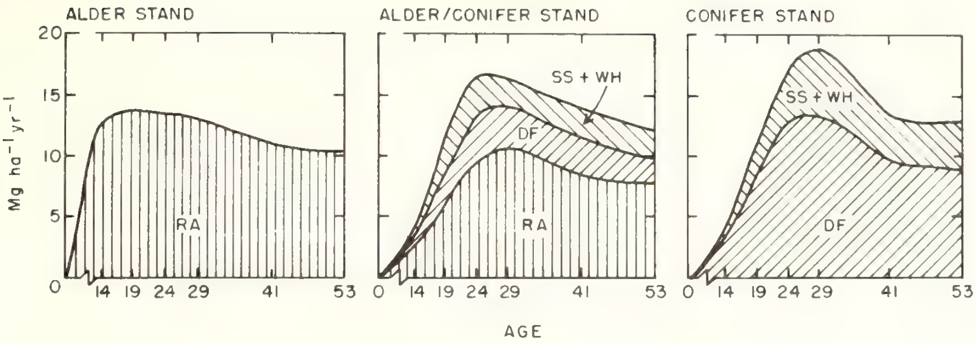

Figure 1. - Aboveground tree net primary production (leaf, stem, and branch growth plus mortality) for the three stand types at Cascade Head. RA = red alder, DF = Douglas-fir, SS = Sitka spruce, WH = western hemlock. Contribution of each species represented by area between curves; uppermost signifies cumulative total.

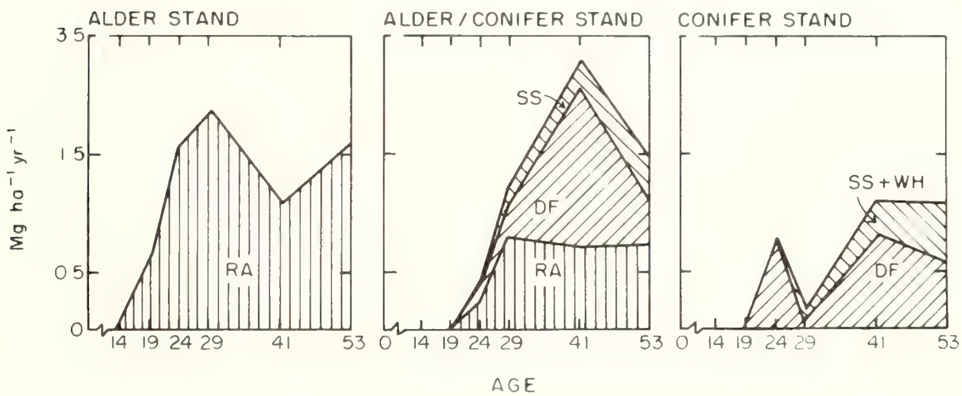

Figure 2. - Aboveground tree mortality for the three stand types at Cascade Head.

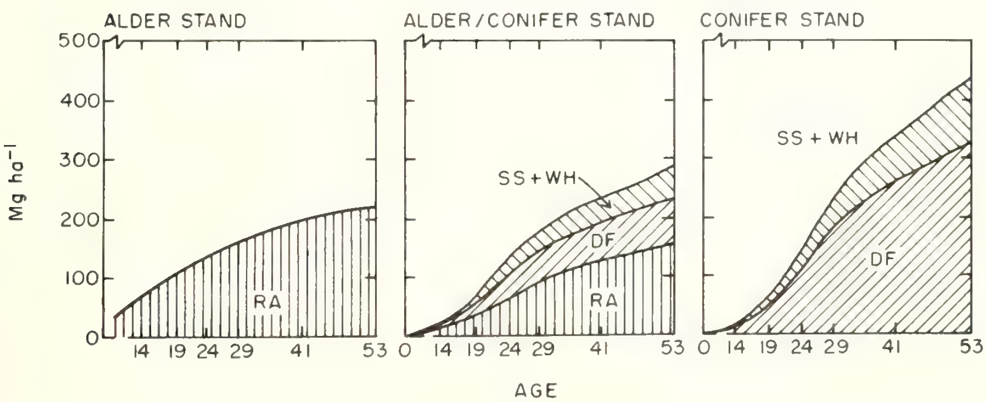

Figure 3. - Aboveground tree biomass [the intergral of figure 1 minus mortality (figure 2)] for the three stand types at Cascade Head.

Patterns in production and tree biomass were similar for the infertile Mount Benson and Wind River sites at age 25 (fig. 4). In both cases, red alder had little effect on Douglas-fir growth, but its presence more than doubled total stand production and biomass. The current Douglas-fir production rate at age 48 at Wind River was about 50% greater where red alder was present; however, the increasing dominance of Douglas-fir had not yet resulted in a substantial increase in Douglas-fir biomass. Where red alder was absent, total ecosystem production was near the bottom of the range reported for Douglas-fir (Grier 1979).

The precise interactions of red alder and conifers in mixed stands will of course vary with site-specific conditions, especially relative stocking densities and dominance. Our comparisons suggest some general trends we think will apply to a broad range of sites. The pattern emerging from our analysis of ecosystem production indicates that mixed stands of red alder and conifers on fertile Site Class I or II areas would not be expected to exhibit higher rates of aboveground net primary production than pure conifer stands. Indeed, greater mortality in mixed stands (especially at high densities) may lead to a decrease in accumulated stand biomass at maturity. Conifer production would probably be much less in mixed stands than in pure conifer stands. In contrast, total ecosystem production in mixed stands on infertile Site Class IV areas may be more than twice that in pure conifer stands at all stages of stand development. Conifer production in mixed stands may be largely unaffected during the early stages, with gains appearing as the stand nears maturity. The timing of conifer canopy dominance and expansion should determine the period of increased conifer growth in mixed stands on infertile sites. Early emergence of conifer canopies should result in early gains in conifer growth. This general site-fertility pattern is consistent with the common occurrence of low growth responses to N fertilization in fertile Site I or II stands and high responses in Site IV stands (Miller and Fight 1979).

Our results underscore the necessity, as noted by Miller and Murray (1979), for stratifying stands according to fertility and for considering complete rotation intractions of species to provide a mechanistic, comprehensive understanding of the potential usefulness of biologically fixed N in maintaining and increasing site productivity.

ACKNOWLEDGMENTS

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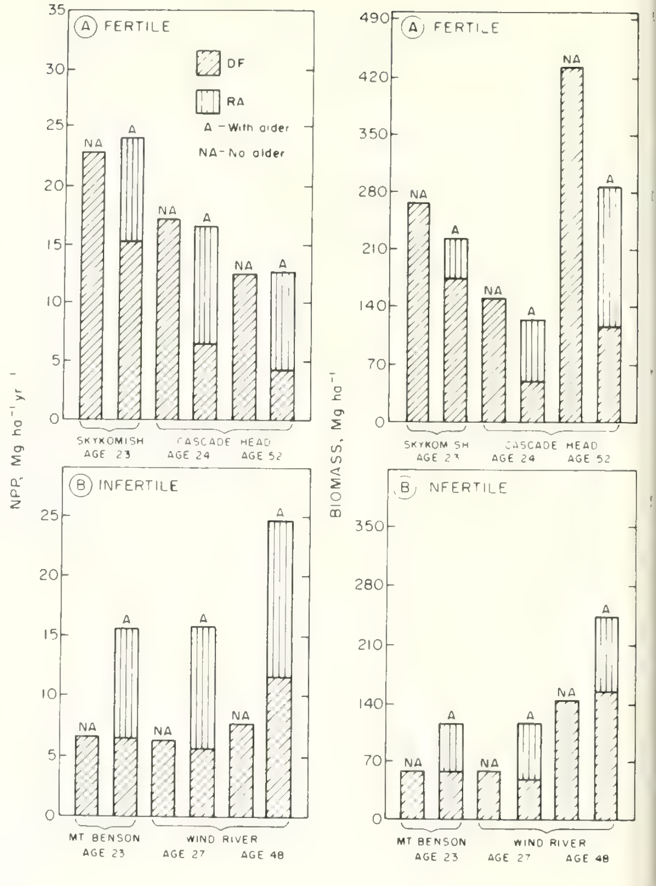

Figure 4. - Aboveground tree net primary production (NPP) and tree biomass for (A) fertile and (B) infertile sites.

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GETTING A GOOD START ON FOREST PRODUCTIVITY

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New techniques for the enhancement of growth in recently established conifer plantations are described. By the use of a controlled release herbicide, competitive vegetation in the vicinity of the seedlings was suppressed for a period of two or more years. This suppression permitted the seedling to get a better share of sunlight, water and nutrients and growth was thereby augmented. The inability of weeds to grow around the seedling then allowed successful fertilization of the juvenile conifers. A new controlled release fertilizer based on a cyclic triazine structure and containing 60% nitrogen is discussed and growth results from its application alone and in conjunction with the controlled release herbicide are presented.

Any measurement of forest productivity has to begin from some arbitrary point in time. In the Pacific Northwest, the date of the outplanting of nursery-grown conifer seedlings constitutes a convenient origin on a scale which may span a century. Over such a lifetime, the productivity of the forest will obviously vary considerably, as indeed will its very definition. Nonetheless, it is axiomatic that without actually securing the establishment of a potential forest in the form of an appropriate stand of seedlings, all else that might ensue is of academic interest only. For this reason, careful attention ought to be given to the seedlings during their first few years of growth after outplanting.

C. BALABAN, J. W. BEER, M. J. COUSIN, D. I. GUSTAFSON, A. W. W. LEE, W. J. McCONNEL, R. A. MIKELS, J. M. MILLER, S. NEOGI and A. YAHIAOUI were all graduate students at the University of Washington during the course of this research. J. DUTKIEWICZ, B. LASKIEWICZ and H. STRUSZCZYK were visiting professors from the University of Lodz, Lodz, Poland. Prof. G. G. ALLAN, to whom enquiries should be addressed at the University of Washington, was the director of the project.

In the Pacific Northwest, the majority of conifer seedlings are 2-0 Douglas-fir stock, and these are now usually planted at a density of about 600 per acre during late fall, winter, or early spring. During the first growing season, some fraction of the seedlings die. The size of this fraction depends on a number of factors and varies tremendously; but it is seldom economically insignificant, especially since all planting is done by hand, often on difficult terrain.

Some mortality can be attributed to competitive vegetation which soon springs up around the conifer seedlings, depriving them of sunlight, nutrients and water. Those seedlings which survive this competition may be substantially retarded in growth, and this effect surely lowers the ultimate productivity of the site.

One theoretical approach to remedying this situation would be to create a vegetation-free zone around each seedling by the application of a herbicide (Allan, Chopra and Russell 1972). Such a chemical would naturally have to be effective in suppressing the growth of a range of plants without damaging the conifer. Moreover,

the biocidal action would be needed for a period of about two growing seasons so that the conifers could become dominant over the invading weeds. Of course, most herbicides are developed, not for forestry, but for agricultural use where only a relatively short period of effectiveness is required. However, by the use of the concept of timed delivery systems, the effective life of any biologically active substance can be significantly extended (Allan, Chopra, Neogi and Wilkins 1971). In this case the herbicide is metered out of a plastic matrix into the environment a few molecules at a time. This incredibly tiny amount of chemical is sufficient to inhibit the germination and growth of weeds which would otherwise later become stiff competition to the conifer seedlings. By this incorporation into a protective, biodegradable, macromolecular structure, the fugitive herbicide, 2,4-dichlorophenoxyacetic acid, which is normally phytotoxic to Douglas-fir seedlings, can be converted into a safer, nonleachable, nonvolatile, nondrifting, nonpolluting granule which remains effective for two growing seasons (Allan, Friedhoff and Powell 1975).

When these granules are scattered on the ground around the conifer seedlings, the invasion of competitive weeds is essentially prevented. Complete elimination of competition is not actually needed, as it has been demonstrated that considerably reducing the normal amount of weeds provides the conifer with a sufficient edge to facilitate its survival (Grover 1967). The data in figure 1 show the effect of various levels of the commercial version of the time-delivery form of 2,4-dichlorophenoxyacetic acid (REFOREST-AID^R, Greenshield of Washington) on the height growth of an operationally planted stand of Douglas-fir seedlings.

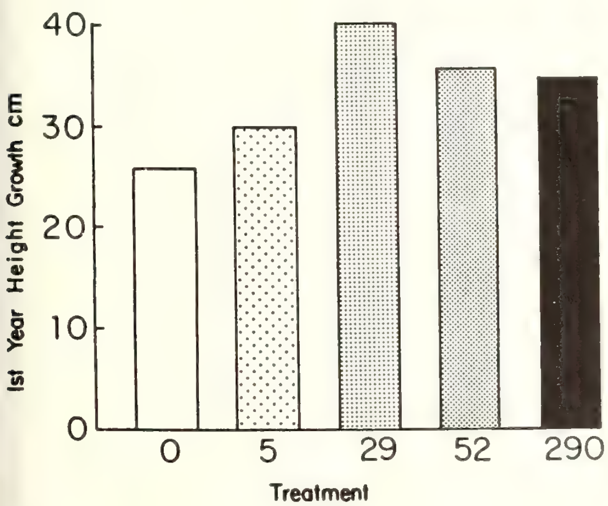

Figure 1. The height growth of Douglas-fir seedlings one year after application of REFOREST-AID^R (0, 5, 29, 52 and 290 g) to an area (2.5 ft^2) around each seedling.

The trees which received the REFOREST-AID^R all exhibited a lower mortality rate than the untreated trees (2 v. 11%) and put on 14, 46, 38 or 35% more growth according to the level of application. Furthermore, the treated seedlings were visually more vigorous and bushier than the controls, which suggests that the traces of the herbicide which reach the seedling's roots can act as a true growth stimulant. This is not surprising, since the auxin effects of 2,4-dichlorophenoxyacetic acid are well known (Wareing 1976). Clearly the productivity of this infant forest has been enhanced by this herbicidal-growth stimulation treatment.

This ability to suppress the vegetation around the seedling also opens another path to increased forest productivity--fertilization. Although the value of the broadcast fertilization of mature trees is now well established (Gessel and Atkinson 1979), previous attempts to supply nutrients to seedlings in this way have been counterproductive (Greaves 1978). Usually the fertilizer applied simply causes the weeds to grow faster, and this causes them to become even better conifer competitors. Seedling growth is thereby actually reduced.

Now, however, when fertilizer is applied to the vegetation-free zone around the seedling, there are no weeds to benefit from the new nutrient source. The conifer seedling is therefore theoretically able to utilize the fertilizer and grow more rapidly thus increasing the productivity of the site. However, fertilizers such as urea or ammonium salts pose some dangers to seedlings because of the osmotic stress they can induce. This is particularly the case in the first year of growth when the seedling may be in the process of recovering from planting shock. Furthermore, these fertilizer materials are very water soluble and can be leached or evaporated away or denitrified before the seedling can utilize them.

A fertilizer in a timed delivery system is therefore clearly called for. Although there are several such fertilizers on the market, most are based on urea-aldehyde resins and have relatively low nitrogen contents. The comparatively expensive precursor aldehydes have no nutrient value. On the other hand, urea can be simply dehydrated by heating and converted into melamine, a high nitrogen (66.6%) low-solubility compound. This substance slowly breaks down in soil (Hauck and Stephenson 1964) to give a fertilizer action which endures for more than two years. In order to supply some initial nitrogen, melamine for fertilizer use (SUPER 60^{TM}, MCI, Donaldsonville, LA 70346) is being marketed as a granule in combination with urea. The concentration of melamine at the soil surface seems to interfere somewhat with the germination of some seeds including western red alder (Alnus rubra Bong.) and vine maple (Acer circinatum Pursh.). Application of melamine (100 g/m^2) to 2-1 Douglas-fir seedlings gave the height and diameter growth response summarized in figures 2 and 3, respectively. Coapplication of both the herbicide and fertilizer gave synergistic effects in the growth

response of both the height and diameter, as shown in figures 2 and 3. The results show for the first time that the productive growth of conifer seedlings can be increased by the appropriate application of fertilizer in conjunction with a growth stimulant-herbicide.

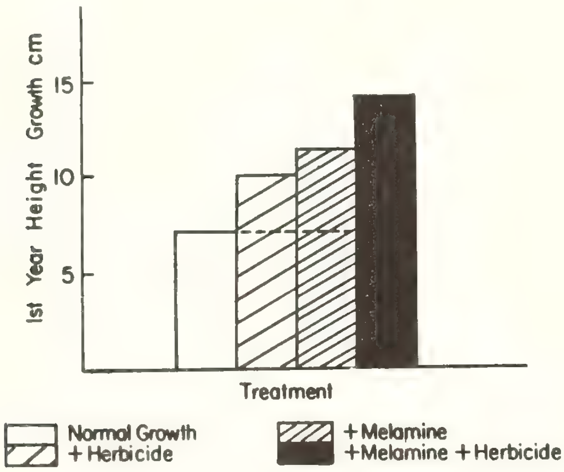

Figure 2. The height growth of Douglas-fir seedlings one year after application of melamine (100 g) and/or REFOREST-AID^R (112 g) to an area (1 m^2) around each seedling.

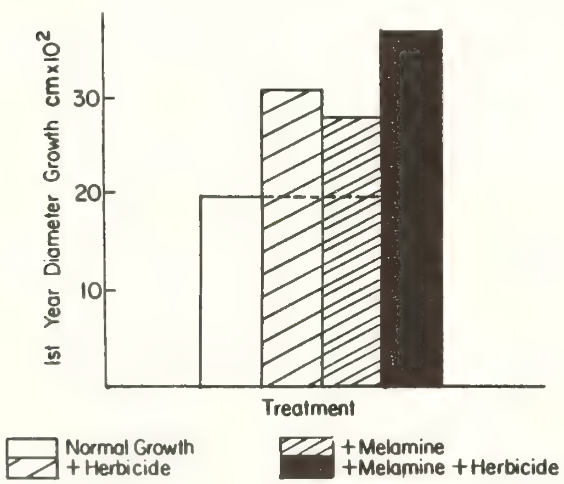

Figure 3. The diameter growth of Douglas-fir seedlings one year after application of melamine (100 g) and/or REFOREST-AID^R (112 g) to an area (1 m^2) around each seedling.

An unexpected consequence of the enhanced productivity achieved in these conifer plantations was the realization that deer browsing is a very important source of productivity-reducing damage. The overall economic loss to deer browsing has been estimated to be several million dollars each year in Washington and Oregon alone (Dimock II and Black 1969). This significant financial impact has led to the development of a variety of systems for the protection of seedlings. These comprise both mechanical and chemical deterrents. The former include several types of plastic meshes, but none are satisfactory because of the physical harm wrought on the tree; harm which is often more severe than the browse damage. Contorted leaders, retarded growth rates and loss of productivity have been frequently observed during field testing of these devices. Another shortcoming of such mechanical devices is that as soon as the conifer leader protrudes from the top, it is totally unprotected and is usually browsed, as it is then the only part of the tree accessible to the deer.

In efforts to circumvent the limitations of mechanical barriers, chemical deterrents have been marketed. All such products are contact repellents and only protect the foliage which has been so coated. New growth, which is highly desirable forage to the deer and which includes the seedling's leader, is not protected.

The essential drawbacks of all presently available systems emphasizes the need for a systemic chemical which will make the entire seedling unattractive to deer. Among the possible candidates, selenium compounds are attractive because plants absorb naturally occurring selenium from the soil and metabolize it as volatile dimethyl selenide and dimethyl diselenide, both of which have a strong garlic-like odor (Vokal-Borek 1979). After a study of the various oxidation states of selenium, it was found the Se compounds with a valency of four are especially suitable for use with conifers (Neogi 1980). These can be smoothly chemically reduced by the seedling to yield odoriferous metabolites at application levels which are nonphytotoxic.

The effectiveness of these metabolites as animal repellents was demonstrated in preference feeding tests by using rabbits. A pellet-type timed-delivery system based on a polymerizable, sparingly soluble salt of selenious acid was therefore designed. Field testing of these soil-applied pellets have shown that at foliage selenium levels of 2-5 ppm, browsing is cut by about half relative to adjacent nonselenized seedlings.

All of the foregoing studies demonstrate that, together, the triumvirate of herbicide/growth stimulant, fertilizer and deer repellent can be expected to make a substantial contribution to the productivity of new conifer forests in the Pacific Northwest and elsewhere when applied in timed-delivery systems.

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SYMBIOTIC NITROGEN FIXATION BY <u>DAVIESIA MIMOSOIDES</u> UNDER <u>EUCALYPTUS</u>

John G. McColl and Robert L. Edmonds

ABSTRACT: *Daviesia mimosoides* is a common understory legume in *Eucalyptus* forests of the Brindabella Range in southeastern Australia, capable of fixing atmospheric nitrogen. Rates of N fixation were measured over a growing season in the field, together with environmental conditions. Greenhouse trials were carried out to elucidate effects of soil moisture, temperature, and light. The acetylene-reduction technique was used to measure N-fixation rates.

Average rates of N fixation in the field varied from about 1-5 µmol C_2H_4/g.hr (fresh weight of nodule), but rates up to 14 µmol C_2H_4/g.hr were measured in optimum controlled conditions. Calculations involving major assumptions indicate that rates approximate 4.5-7.0 kg/ha N fixed on a yearly basis. Average N-fixation rates were not correlated with average soil moisture, average soil temperature between sampling, or nodule size.

Fixation rate decreased with soil moisture to about -100 bar tension, with a marked depression at about -60 bar. Within the normal field range of soil moisture, there was little correlation of moisture with average N-fixation rate. N-fixation rates were similar in the temperature range of 20 to 30° C, but were depressed by either low or high temperatures (<10° C or <30° C). Diurnal fluctuations in N-fixation rates were not correlated with solar radiation, but rates were limited by high midday temperatures.

INTRODUCTION

Nitrogen is often the limiting factor of growth in forests, and thus much attention has been focused on nitrogen cycling processes and possible effects of disturbances (harvesting, fire, defoliation, etc.) that may disrupt such processes. There has also been increased interest in nitrogen inputs to forest ecosystems, particularly as costs of nitrogenous fertilizers have increased dramatically. The role of nitrogen-fixing plants in forest ecosystems is therefore now receiving much attention.

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In Australia, estimates of nitrogen fixation using the acetylene-reduction technique have been made for native species such as the cycad *Macrozamia riedlei* (Grove et al. 1980; Halliday and Pate 1976), and the legumes *Acacia pulchella* in Western Australia (Monk et al. 1981) and *Acacia holosericea* (Langkamp et al. 1979, 1982) in the Northern Territory. Lawrie (1981) also estimated nitrogen fixation in 10 legume species in Victoria. Fixation rates range from 0.004 to 18.8 kg N/ha.yr in these studies. Other estimates of nitrogen fixation have been made "by difference," using the mass balance approach in cycling models.

Daviesia mimosoides, a legume, is often a dominant understory species in dry-sclerophyll *Eucalyptus* forests of the Brindabella Range, Australia Capital Territory, but estimates of its nitrogen-fixing capability have not been made.

The aim of this study was to document nitrogen-fixation rates for this native species in the field and to investigate environmental factors that control fixation rates.

STUDY AREA

The site was located on a red earth-kraznozem soil derived from parent material of highly weathered Ordovician sediments. Our study site was in a E. dives-E. dalrympleana forest community. In the general area, E. pauciflora forests occupy easterly aspects at elevations above about 1 200 m, and E. dives-E. dalrympleana forest communities occur on exposed ridges with northerly aspects. E. delegatensis forests occur on moist, cool, southerly aspects above about 1 000-m elevation. Daviesia mimosoides occurs in all forests mentioned, but is most dense on exposed aspects and usually replaced by another leguminous shrub, Acacia dealbata, in the moist valleys supporting E. delegatensis.

The subalpine climate is characterized by cold winters (mean maximum and minimum temperatures in July are 4^{o} C and -1^{o} C) and warm summers (24^{o} C and 10^{o} C in January); mean annual rainfall is about 1 150 mm with no seasonal pattern, but hot dry periods of 6-8 weeks are common during December to February (from records of Official Weather Stations). Winter snow is common, but the soil rarely freezes. Soil temperatures and moisture regimes at the study site for the study period are given in figures 1 and 2.

METHODS AND MATERIALS

Field Acetylene-Reduction Assay

The acetylene-reduction technique used was similar to that used by Lawrie (1981). Small D. mimosoides seedlings were dug with a garden fork. Seedling shoots were 160±10 ($\bar{x}$±S.E.) mm high and weighed 0.61±0.10 g oven dry; roots weighed 0.30±0.05 g. Intact roots were carefully cleaned of soil (without washing). Sampling was carried out 11 times over the period October 1981-May 1982. On each sampling date about 75-100 plants were sampled, and roots with attached nodules were placed in 28 ml McCartney bottles. About 10-20 nodules per bottle were collected, and a total of nine bottles were filled each sampling date.

Sampling was carried out between 12:00 p.m. and 1:00 p.m. The 28 ml bottles were sealed with rubber stoppers and a gas mixture containing 10 percent C_2H_2, 20 percent O_2, and 70 percent argon was introduced three times between evacuations to 58c bar using a hand-pump. Incubation periods varied between 1-2 hours at field temperature by packing the bottles in freshly collected field soil. Supplementary tests indicated that C_2H_4 production was linear for 3 hours. Gas samples were transferred to 10-ml tubes for subsequent analyses. Nitrogen fixation was estimated using the acetylene-reduction technique. C_2H_4 production was measured by gas chromatography; appropriate blanks and standards were also assayed.

Following analyses of C_2H_4 production, the nodules were carefully removed from the roots. Nodule weights (wet and dry) and nodule numbers were then determined. Nitrogen-fixation rates are expressed in this report as production of C_2H_4 per fresh weight of nodule per hour.

Soil temperature at the 5-cm depth was taken at each sampling time. A maximum-minimum thermometer at the 5-cm depth gave extreme temperatures in the soil between sampling dates. Soil moisture was also determined at each sampling time; gravimetric measurement was made using seven replicates of the 0 to 10-cm soil depth, this being the approximate rooting zone of the D. mimosoides seedlings.

Soil Moisture Experiment

Seedlings with nodules lifted from the field, as previously described, were used in a greenhouse environment where soil moisture levels were controlled. Seedlings having at least one nodule were planted in black plastic tubes, approximately 180 cm high and 75 cm wide in 600 g of soil collected from the 10-cm depth at the same field site. This surface soil had the following particle-size distribution in the <2 mm fraction: 17 percent coarse sand; 32 percent fine sand; 23 percent silt, and 28 percent clay. Average bulk density was 0.9 g cm^{-3}, and there were 25 percent by weight of particles >2 mm diameter. Two seedlings per pot were planted and immediately watered. These plants were then transplanted to the greenhouse and grown under optimum moisture conditions for about two weeks. They were then transferred to a controlled temperature greenhouse where the day/night temperatures were held at 25^{o} C/20^{o} C, respectively.

All containers were thoroughly watered, then triplicates of the plants harvested and N-fixation rates assayed at various soil moisture levels as the soil dried. The first harvest was made 1 day after saturation (i.e., at "field capacity") when the soil moisture content was about 50 percent (oven-dry weight basis), and periodic harvesting continued over a period of about 2 weeks, during which time soil moisture levels dropped to about 7 percent. At each harvest, roots with intact nodules were placed in assay flasks, and analyzed for C_2H_4 production as previously described for the sampling of the field material. Gravimetric soil moisture determinations were made for each replicate. These soil moisture measurements were converted to units of tension, following construction of a soil moisture/tension curve for the soil using a tension plate apparatus.

Temperature Experiment

Seedlings from the field were also set up in a greenhouse as outlined above. Once the seedlings

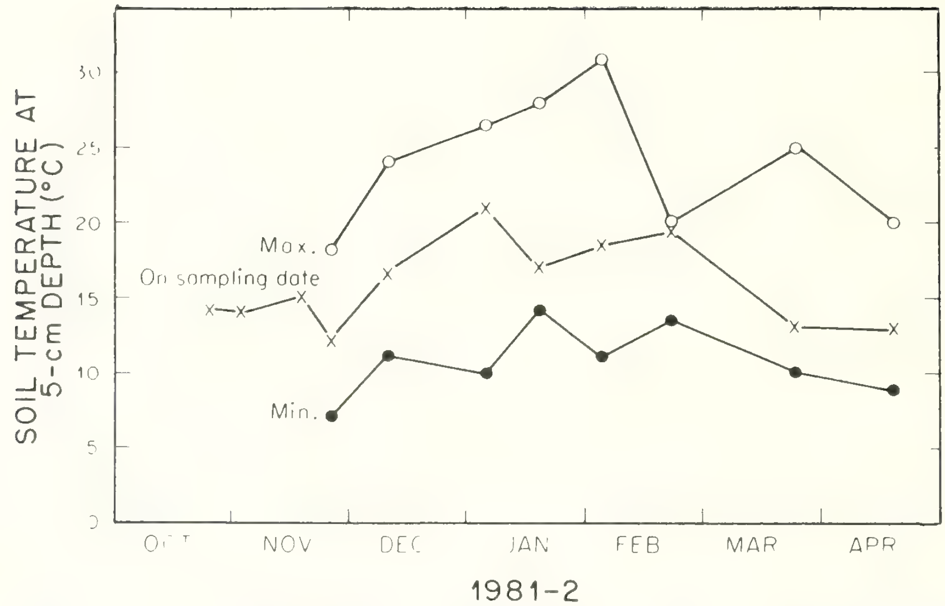

Figure 1.--Soil temperatures (maximum and minimum between sampling dates, and on sampling date) at the 5-cm depth, over the study period in 1981-82, in the Brindabella Range, Australian Capital Territory.

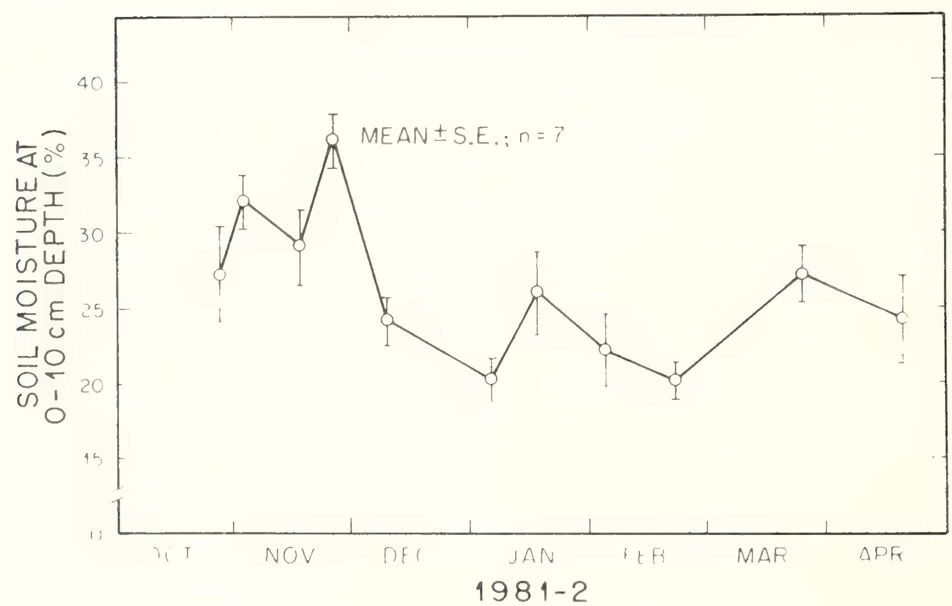

Figure 2.--Soil moisture in the 0 to 10-cm depth, over the study period in 1981-82, in the Brindabella Range, Australian Capital Territory.

were well established, 5 replicate containers (each containing two seedlings) were placed in controlled-environment chambers (1,000-ft candle-power for 16 hours/day) where soil moisture was kept at optimum levels and where temperatures were held at the following levels: 5, 10, 15, 18, 24, 30, and 35° C. No distinction was made between day and night temperatures. The plants were left in these temperature treatments for 3-4 days prior to harvesting and assaying N-fixation rates as already described.

Diurnal-Fluctuation Experiment

Seedlings from the field were set up in containers as outlined above. Two replicate containers, each containing two seedlings, were assayed at time intervals throughout a 24-hour period. The plants were left in the greenhouse throughout the pretrial period and during the diurnal study itself. Throughout the 24-hour study day of March 3, 1982, solar radiation was measured above the greenhouse; soil temperature within the pots and air temperature inside the greenhouse were also measured. The study day was overcast in the early morning and late afternoon, but clear and sunny at midday. Harvesting and assaying of N-fixation rates were made as already described.

RESULTS

Nodule Characteristics and N fixation in the Field

Daviesia mimosoides seedlings in the field had few nodules and many plants sampled had none (fig. 3). Nodules were generally located on new lateral roots close to the soil surface and were most abundant in locations where soil moisture was higher; e.g., in slight depressions and where soil organic matter was relatively greater. Average weight per nodule varied from about 1.00 to 1.75 mg (oven-dry), and 3.20 to 6.50 mg (fresh) (fig. 4). Nodule weight was not significantly correlated ($p<0.05$) with the percentage of plants that had nodules (fig. 3).

Average rates of N fixation varied from about 1-5 µmol C_2H_4/g nodules/hr (on a fresh weight basis) (fig. 5). For two sampling collections on November 26 and December 1, nodules were segregated prior to N-fixation assays into nine size classes covering a total range of 1.5- to 16.00-mm length. No relationship was found between N-fixation rates and mean length of nodule.

Rates of N fixation were also plotted against average nodule moisture content for 75 samples collected over the study period. No correlation existed between N-fixation rate and nodule moisture content.

Effect of Soil Moisture

In this trial and in the other greenhouse trials where the plants were grown under optimum conditions prior to treatment, rate of nodule formation was great and many plants had dozens (and sometimes hundreds) of round-shaped, white nodules which developed on new roots.

Mean rates of N fixation are plotted against soil moisture tension in figure 6. Between soil moisture tensions of about -0.1 to -60.0 bars, N-fixation rates were relatively constant (between 2-6 µmol C_2H_4/g.hr) but at very low soil moisture contents (∽60 bars) N-fixation rates dropped markedly. At these low soil moisture contents, the plants also wilted beyond recovery. At high soil moisture contents (<-0.1 bar tension), N-fixation rates increased dramatically to over 14 µmol C_2H_4/g.hr. As the soil approached saturation (near -0.001 bar tension), N-fixation rate dropped, presumably because of increasing anaerobic conditions.

Effect of Temperature

N fixation occurred over a fairly wide temperature range, with a high plateau between 20° C-30° C (fig. 7). The N-fixation rate decreased abruptly over 30° C, but less abruptly on the colder side; it was not until 5° C that average rates dropped below 2 µmol C_2H_4/g.hr (fig. 7). Following analysis of variance, the least significant differences between treatment means ($p<0.05$ level) were calculated. The following four groupings of temperature treatments (°C), were those that had significant differences in mean N-fixation rate: (5,35), (10,15,24,35), (15,18,24), and (18,24,30). In this temperature trial, both roots (in the soil) and shoots were at the same constant day/night temperature.

Diurnal Fluctuations

There were marked changes in N-fixation rates over the 24-hour period studied, and rates did not correlate with either temperature regimes or incident solar radiation (fig. 8). In fact, the maximum rate of N fixation occurred near midnight, and minimum rates occurred in early afternoon. Soil temperatures rose abruptly to over 32° C during the midday period when the sky was clear and sunny, and soil temperature exceeded air temperature because of heat absorption by the black-colored containers and dark soil surface. N fixation was apparently depressed by high temperatures during early afternoon (fig. 8).

DISCUSSION

Although the occurrence of nodules on roots of Daviesia mimosoides was sparse in the field, with only 50-80 percent of plants having any nodules at all (fig. 3), it was obvious from the greenhouse trial that nodule production could be readily increased under optimum temperature and moisture conditions. Plants grown in greenhouse

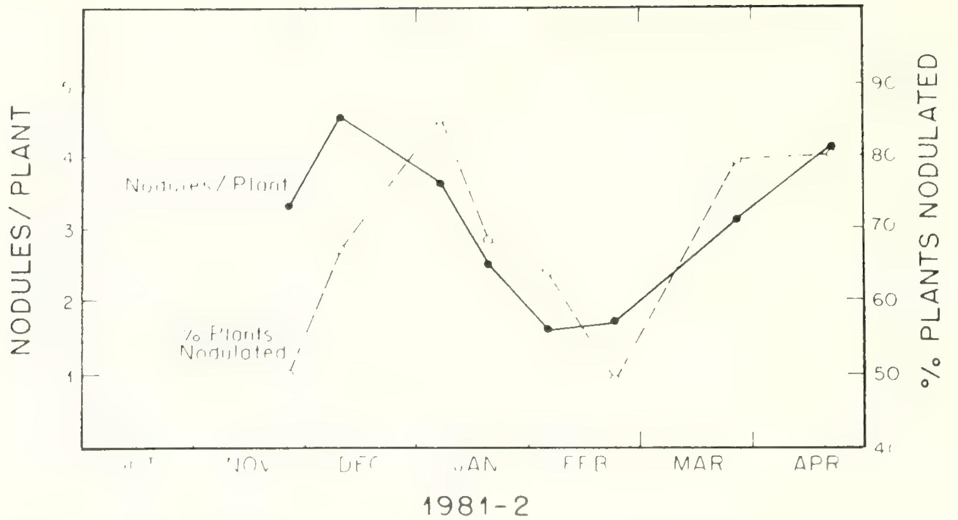

Figure 3.--Average nodules per plant and percentage of plants with nodules over the study period in 1981-82; Daviesia mimosoides in the Brindabella Range, Australian Capital Territory.

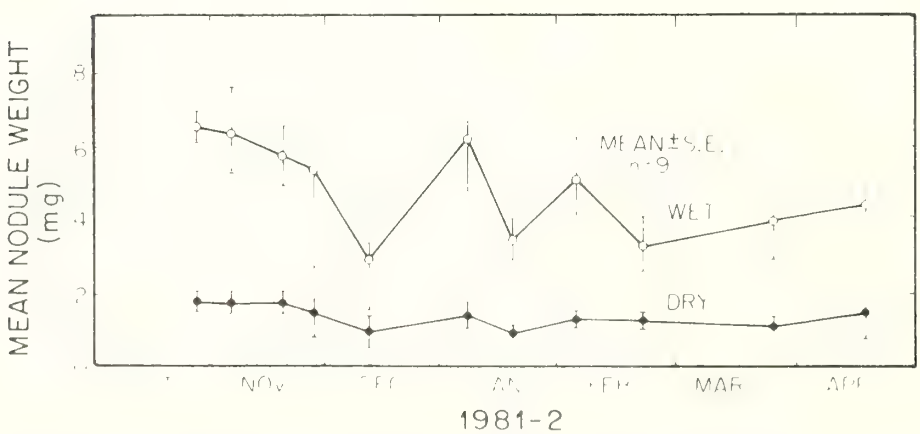

Figure 4.--Mean wet and dry nodule weights of Daviesia mimosoides over the study period in 1981-82, Brindabella Range, Australian Capital Territory.

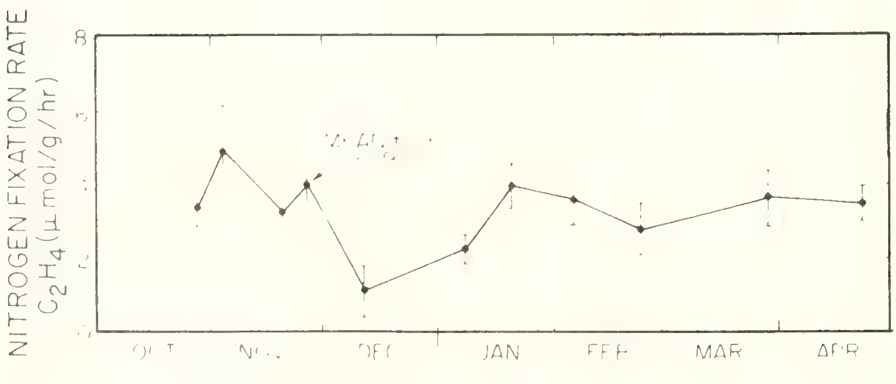

Figure 5.--Nitrogen-fixation rates of Daviesia mimosoides nodules over the study period in 1981-82, Brindabella Range, Australian Capital Territory.

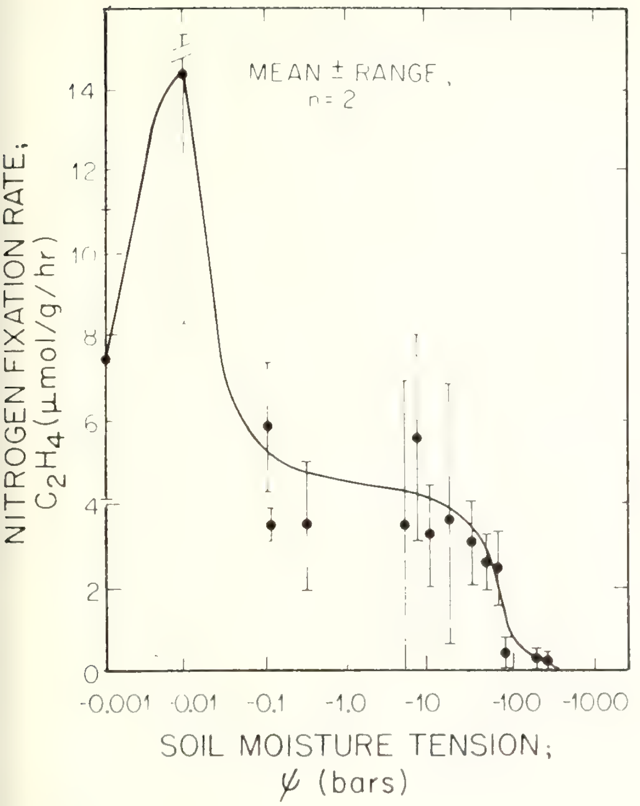

Figure 6.--Variation in nitrogen-fixation rate of Daviesia mimosoides nodules because of soil moisture tension, under controlled environmental conditions.

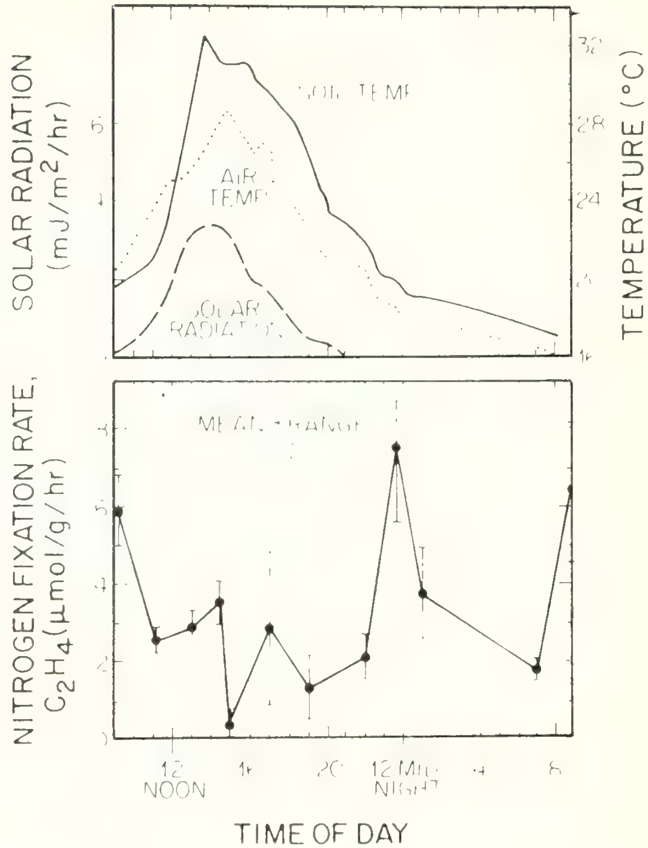

Figure 8.--Diurnal fluctuations in nitrogen-fixation rate of Daviesia mimosoides nodules, and in soil temperature, air temperature, and solar radiation (outside greenhouse) on the study day of March 3, 1982.

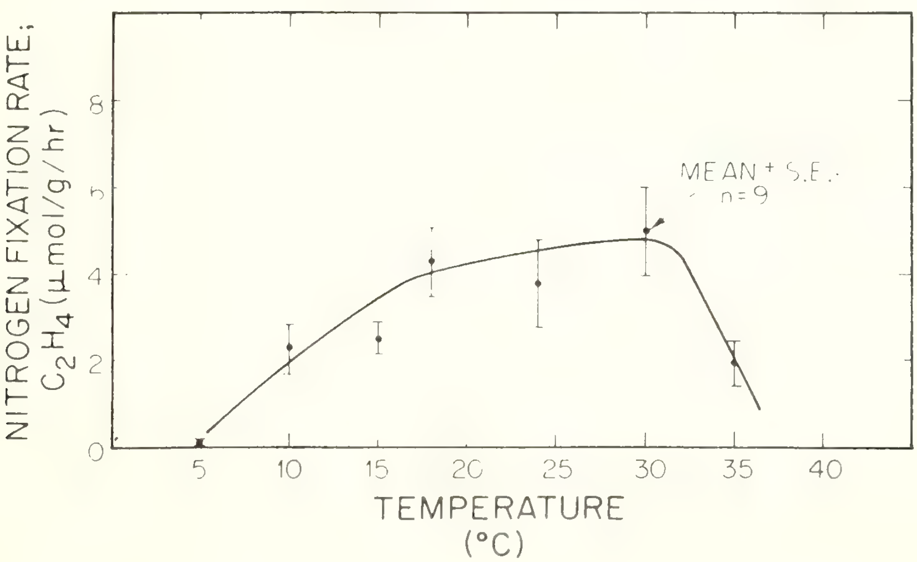

Figure 7.--Variation in nitrogen-fixation rates of Daviesia mimosoides nodules because of temperature, under controlled environmental conditions.

conditions in native surface soil produced dozens of nodules on new roots. Most N-fixation rates in the greenhouse trials, however, fell in the general range of rates measured in the field, giving credibility to extrapolation of greenhouse trial results to field conditions.

Under a wide range of soil moisture conditions in the field, N-fixation rates were relatively constant (fig. 6), and it was not until plants wilted without recovery (following subsequent rewatering) that rates dropped markedly. This illustrates the hardiness of the nodules to desiccation, and the remarkable ability to continue N fixation even at very low soil moisture levels. It is also apparent that nodules of D. mimosoides have the ability to respond rapidly to favorable conditions; i.e., that increases in both nodule numbers and N-fixation rates occur when soil moisture levels are favorable. Under ideal soil-moisture conditions, N-fixation rates were elevated to 14 µmol C_2H_4/g.hr compared to the average 1 to 5 µmol C_2H_4/g.hr under normal field conditions. Similarly, Monk et al. (1981) found field rates in the range of about 3.0 to 7.0 µmol/g.hr for Acacia pulchella var. glaberrima in Perth, West Australia.

Minimum soil temperature at the 5-cm depth never rose above 14.0° C (fig. 1), and minimums in winter at our study site would be expected to drop to 0° C. The main effect of temperature in the field would be reduced N-fixation rates below about 15° C (fig. 7). At the other extreme, soil temperatures in the field that would be high enough to limit N fixation are rare, although the maximum soil temperature rose to 31° C between January 20 and February 5 (fig. 1).

The interaction between temperature and moisture regimes also would affect N-fixation rates, and the temporal variations in rates in the field (fig. 5) are probably due to such interactions.

The diurnal pattern of N fixation noted with the highest peak at midnight (fig. 8) was somewhat unexpected at first, as other similar studies have shown a correlation between solar radiation and rates of N fixation with a peak at 12:00 p.m. to 2:00 p.m. (e.g. Lawrie 1981) under moderate temperature conditions. If temperatures had been more moderate (i.e., not risen to >30° C), such a correlation with solar radiation may have been obtained. The supporting data from the greenhouse temperature study (fig. 7) substantiate the noted decrease in N-fixation rates at temperatures over about 30° C. McNiel and Carpenter (1979) also report a N-fixation peak at 8:00 p.m. in Alnus glutinosa when daytime temperature approached 30° C.

Redistribution of photosynthate in this woody species (especially in older plants in the field that grew from sprouting root stocks) would also complicate a simple correlation between production of photosynthate (and thus solar radiation) and rates of N fixation in nodules (Wheeler 1971).

Because ecosystem models of nitrogen cycles generally lack direct measurement of N inputs, it is tempting to calculate total input of N from data of N-fixation rates. Such mean estimates have large error estimates, however, and involve some gross assumptions that are unsubstantiated until further detailed studies are made. Nevertheless, at the risk of being quoted without qualification, we have calculated approximate inputs of nitrogen from N-fixation rates using the following assumptions:

Ratio of C_2H_2 reduced to N_2 fixed = 3:1,
Days/yr when average fixation occurs = 270,
Hours/day when average fixation occurs = 12,
Average fixation per day (µmol C_2H_4/g fresh nodules) = 38 (range was 3 to 79)
Average weight/wet nodule = 5 mg,
Nodules/ha (low plant density) = 8.792×10^6, and
Nodules/ha (high plant density) = 12.811×10^6.

The nodules/ha were calculated from:

$$\frac{\text{No. nodules on small seedlings}}{\text{Dry wt. of leaves of seedlings}} = \frac{\text{Number of nodules/ha in field}}{\text{Dry wt. of leaves/ha}^{1/}\text{ in field}}$$

Using these assumptions, average N fixation in D. mimosoides was calculated to account for about 4.5 to 7.0 kg/ha.yr of nitrogen input to the forest ecosystem, the range given being dependent on plant density. Similarly, averages of 6.4 kg/ha.yr were estimated for N fixation by Acacia holosericea (Langkamp et al. 1982), 2.2 kg/ha.yr for A. pulchella var. glaberrima (Monk et al. 1981), and 0.8 kg/ha.yr for A. mearnsii (Lawrie 1981). Future research is needed to determine how much of the N input is subsequently tied up in the subcycling of nitrogen by the D. mimosoides understory itself, and when and how much becomes available for use by the forest stand.

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1/ Derived from another study in the same area over a wide range of plant size (J. Raison, personal communication).

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REVIEW OF SECOND ROTATION SILVICULTURE OF P. RADIATA PLANTATIONS IN SOUTHERN AUSTRALIA: ESTABLISHMENT PRACTICE AND EXPECTATIONS

Ross O. Squire

ABSTRACT: The retention of litter and logging residue as a source of nutrients and organic matter for the next crop, as well as a mulch to conserve soil moisture, are recognized as primary factors influencing the productivity of successive crops of radiata pine planted on sandy soils, and are also likely to be relevant, though perhaps to a lesser extent, on more fertile soils. The influence of site and stand characteristics on the implementation of these principles is discussed with special reference to radiata pine on infertile sands.

On infertile sands, improved early growth in the second rotation has been achieved from a variety of practices. In each case, the improvement appears to be largely due to increases in both the availability of water (weed control and/or mulching) and nitrogen (inputs from either fertilizer, fixation by legumes, or from accelerated mineralization of organic N in logging residue). The significance of these early results to productivity over the full rotation is discussed in relation to soil water availability and studies of the influence of water and nitrogen treatments on the water-use efficiency of radiata pine seedlings.

INTRODUCTION

Pinus radiata D. Don is the most extensively planted coniferous species in Australia, and the policy of the Australian Forestry Council (1975) is to aim for a total softwood plantation area of nearly one million hectares by the year 2000. Most of these plantations will be in southeast Australia on soils ranging from sands to clay-loams, often of only moderate fertility by agricultural standards, and where the average rainfall may be less than 800 mm per annum. Also, these areas are characterized by summer drought, high solar radiation, high air temperatures, and low atmospheric humidities. Despite these limitations, *P. radiata* in these dry environments may produce a biomass well above the previous native forest (Florence and Shepherd 1975). Australia has a very limited native forest resource, however, and with an expanding public demand for recreational and environmental values from these forests, the wood supply is becoming increasingly dependent upon a limited plantation area, predominantly of *P. radiata*.

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This pressure, combined with earlier evidence from South Australia (Keeves 1966) of a substantial decline in productivity between first rotation and second rotation stands of radiata pine on coarse-textured, infertile sands, provided the impetus for a major research effort by various organizations to understand the factors limiting and influencing site productivity, particularly on soils similar to those studied by Keeves (1966). By the mid-1970s, Woods (1976), following the philosophy of Waring (1972), had shown that substantial increases in early growth could be achieved in the second rotation, using intensive cultural practices involving cultivation and application of herbicides and fertilizers. More recently, the work of Flinn (1978), Farrell et al. (1981), Squire et al. (1979), and Woods (1980), has identified conservation of organic matter and nutrients (especially N) as the primary factors influencing long-term productivity of sandy soils. These factors are also likely to be relevant, though perhaps to a lesser extent, on more fertile soils.

This knowledge has required forest managers to carefully assess the possible long-term effects of current establishment practices on nutrient reserves and soil organic matter. In particular, attention has been directed to the burning of litter and logging residue, a practice that has been used extensively and that has obvious advantages in facilitating movement of people and equipment, such as plows and planting machines. It also reduces the risk of wildfire and eliminates natural regeneration.

Squire and Flinn (1981) calculated that burning the logging residue after a first rotation of 40 years (mean annual increment (m.a.i.) ≅ 29 m^3 ha^{-1}) on an infertile sand would remove about 745 kg ha^{-1} N, and according to Woods (pers. comm.)[1/] replacement of the N plus phosphorus and trace elements would cost, at 1982 levels, about \$900 ha^{-1}. Although the effects of nutrient losses of this order on nutrient availability to the second crop are not yet understood, the evidence of a large proportional loss in total reserves over a single rotation is of concern. Consequently, the principle of retaining litter and logging residue as a source of nutrients as well as a mulch to conserve soil moisture and reduce the need for herbicides, is now widely accepted. On infertile sandy soils, where it is also essential to conserve soil organic matter (Flinn et al. 1980), the practice is likely to be the only reliable means by which site productivity can be maintained.

Implementation of these principles is influenced by site and stand characteristics. In this paper, the influence of these constraints is illustrated by reference to two contrasting *P. radiata* ecosystems: one on steep, fertile, clay-loam sites, and the other on flat, infertile, sand sites. The paper also reviews some early results and discusses their long-term implications.

CURRENT PRACTICE

Fertile Clay-Loam Sites

Steep, fertile, clay-loam sites are common at Myrtleford (latitude 36°34' S., longitude 146°44' E.) in the State of Victoria, where there are more than 26 000 hectares of softwood plantations. In many instances, the soils are skeletal on the ridges, but elsewhere are well developed and several meters in depth. Slopes of 20 to 30 degrees are common. The area has a mean annual rainfall of around 1 300 mm with a clear summer minimum and winter maximum. Snowfalls occur infrequently.

In the first rotation, these sites commonly produce a m.a.i. of about 22 m^3 ha^{-1} over a 35- to 40-year rotation. In most cases these first rotation stands have been thinned several times, often with great difficulty, using horses to extract individual logs. At final felling, these relatively open stands (≅ 200 stems ha^{-1} and ≅ 20 $m^2 ha^{-1}$) carry prolific quantities of seed.

The selection of re-establishment techniques is influenced by two very important factors:

1. Dense crop (often > 20 000 stems ha^{-1}) of natural regeneration will develop unless the logging residue is completely burned by a relatively intense fire.

2. On steep slopes (20 to 30 degrees), mechanical systems for either reducing logging residue or planting cannot be considered. Thus, the residue cannot be crushed, and the fresh residue, in particular, will seriously limit the movement of people.

The use of a relatively intense slash burn in the autumn after logging, followed by hand planting, is a solution to both of these problems, but at the expense of conservation of nutrients and organic matter. The only feasible alternatives are either to remove the natural regeneration and plant or to retain the natural regeneration for the second crop. There are considerable problems in either removing the natural regeneration or thinning it to manageable densities of high quality plants. Aerial spraying with herbicides during the first year after logging is likely to be the only cost-effective method for removing natural regeneration. The application of herbicides, such as amitrole, using a helicopter is being evaluated; but for this method to be effective, foliage must be wetted to drip-off point, and so far, this has not been achieved in practice (Minko, pers. comm)[2/]. There are two main limitations to the use of natural regeneration

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1/ Woods, R. V. Former Senior Forester, Establishment, Woods and Forests Department, South Australia.

2/ Minko, G. Senior Research Officer, Forests Commission, Victoria, Australia.

for the second crop: (1) to facilitate movement of people, thinning should be delayed until residue decomposition is well advanced, and even then, it is likely to be expensive; and (2) earlier studies (Minko, pers. comm.)[2/] have indicated that the resultant stand is likely to contain a very high proportion of poor quality stems. For these reasons, current practice is to reduce the logging residue by slash burning in the autumn, and hand plant with 1-year-old seedlings in the winter.

This case study underlines the potentially overriding influence of a site characteristic, slope in this instance, on the implementation of residue retention principles. On these soils, which have a high clay content and therefore a good capacity to retain both nutrients and water, it is considered that replacement of nutrients lost by harvesting and other site disturbances, may be sufficient to sustain productivity.

Very carefully monitoring the impact of current practice on both nutrient losses and growth is still important, however. Nutrients removed during harvesting and volatilized during burning can be estimated adequately using existing data as outlined by Squire and Flinn (1981). Further losses will occur through transport as either dissolved or particulate matter; and these losses are likely to be increased, but to an unknown extent, by both burning and soil disturbance during logging. Accordingly, two long-term studies have been undertaken to monitor:

1. The impact of plantation establishment practices on the quantitative levels of nutrient outputs in stream water compared with inputs of rainfall (Flinn et al. 1979a).

2. First rotation and second rotation growth on the same sites (Minko, pers. comm. see footnote 2) using the techniques described by Squire et al. (1979) for a similar study at Rennick in southwest Victoria.

Initial results are available for the hydrologic study (Flinn et al. 1979a) covering the calibration period prior to conversion of existing native eucalypt species to a plantation of radiata pine. These results showed that the concentration of nutrients in both rainfall and streamflow was very low. The nitrogen and phosphorus concentrations of streamflow were especially low and often close to, or below, the limits of detection; e.g., the average N balance for three catchments of Cropper Creek in 1977 was (0.319 input - 0.12 output) = 0.307 kg $ha^{-1}.yr^{-1}$. These initial levels will be used as standards to assess the treatment effects during and after conversion to pines. This, with estimates of harvesting and burning losses, will provide a guide to the net nutrient losses from the ecosystem as a result of disturbance, and therefore, of the likelihood of a reduction in site productivity. Ultimately this study will focus on the effect of disturbance associated with the establishment of a second rotation pine crop.

Infertile Sand Sites

Flat-to-undulating, infertile sand sites occur extensively in southeast South Australia and neighboring areas in Victoria (latitude 37°49'S., longitude 140°59' E.), where over 100 000 ha of P. radiata plantations have been established. These plantations are growing on aeolian sands which are infertile compared to many forest soils and contain very low levels of organic matter in the surface horizons. For example, Caroline sand, a common soil in this region, contains 1.6 percent organic carbon and 0.03 percent total N in the surface 0 - 20 cm (Hopmans et al. 1979). The area has a mean annual rainfall of about 800 mm with a pronounced summer minimum and winter maximum. Soil moisture availability, especially in summer-autumn, and nutrient availability, particularly N, are major factors influencing the growth of radiata pine on these soils (Ruiter 1979, Squire et al. 1979).

In the first rotation these sites can achieve a m.a.i. of up to 30 m^3ha^{-1} over a 40-year rotation, but values of 20-25 m^3ha^{-1} are more common (Lewis et al. 1976). Until the late 1970's, with few exceptions, the establishment of the second crop involved the use of high-intensity fires to reduce logging residue (Flinn et al. 1979b, Woods 1980). As previously discussed, there is now good evidence that this practice contributed in large part to the average 25-30 percent decline in productivity of these sites in the second rotation as measured by Keeves (1966). Since the mid-1970's, cultural practices such as cultivation and application of herbicides and fertilizers have been used extensively in an attempt to maintain productivity at levels of the first rotation (Woods 1980).

The principle of retaining litter and logging residue as a source of nutrients and organic matter for the next crop, as well as a mulch to conserve water, is well accepted in this region (Farrell et al. 1981, Woods 1981). But, as in northeast Victoria, its full implementation is not always feasible. Current practice is therefore varied, reflecting effects of operational and economic factors and also the management requirements of the various government and private forest owners in the region. Three very different practices, identified according to the predominant source of N in the early years of the second rotation (Nambiar and Woods, pers. comm)[3/], will be described together with a brief account of early growth responses.

Nitrogen supplied from fertilizer.--This practice has been applied extensively in South Australia since 1976. Logging residues are generally

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3/ Nambiar, E. K. S. Research Scientist, Division of Forest Research, Commonwealth Scientific and Industrial Research Organization, Mount Gambier, South Australia, Australia.

heaped into windrows and then burned (windrow burning). A sequence of annual fertilizer applications (NPK + trace elements) is initiated about 1 month after planting and provides about 300 kg ha^{-1} N during the first 48 months of the rotation. A high number of applications is necessary to avoid toxic effects of N (N-burn) on young root systems (Woods 1976). Two chemical weed control treatments (amitrole + atrazine) are applied in the first 12 months after planting.

The above sequence (Maximum Growth Sequence, Woods 1976) has produced a three-fold increase in biomass by age 3 years. The maximum growth sequence was designed to maintain optimum foliar nutrient levels and a high rate of crown expansion. Generally, it accords with the principles recently enunciated by Ingestad (1979) that nutrient additions should be adjusted exponentially with time and with the growth of seedlings to achieve maximum growth potential (Woods 1981). Furthermore, Woods (1981) has reported that N fertilizer (200-300 kg ha^{-1}) applied to second rotation stands at mid-rotation also substantially improves growth. Results to date suggest that the maximum growth sequence, perhaps supplemented by mid-rotation fertilizing, has the potential to sustain and possibly even improve the productivity of these sandy soils (Woods 1981). Further monitoring is necessary to confirm this potential.

There are plans to eliminate windrow burning and to crush logging residue in its original location once the large smashed waste logs that presently impede efficient crushing are disposed of by chipping for pulp or fuel (Woods, pers. comm. see footnote 1). Also, trials have been established (Farrell et al. 1981, Woods, pers. comm.) to evaluate crushing/maceration treatments in combination with herbicide applications and the fertilizer regime of the maximum growth sequence.

Nitrogen supplied from legumes.--The capacity of nodulated species to add N to a site is high and may exceed 100 kg $ha^{-1}.yr^{-1}$ for a period of up to 5 years depending on the suppressive effect of the developing pine crop (Gadgil 1971, Richards and Bevege 1967). N fixation by legumes therefore represents a potentially important pathway of N replacement in the ecosystem and helps to maintain existing low levels of soil organic matter. Replacement of other elements, and perhaps supplementary N additions, will still be necessary but there could be substantial savings in the material cost of N (≅ \$250 ha^{-1} at 1982 levels for the maximum growth sequence described above) (Woods, pers. comm. see footnote 1).

A potential major problem with this approach, especially in drier areas, is that competition for soil moisture may seriously affect survival and growth of both pines and legumes. Cooperative studies in South Australia, however, involving the Division of Forest Research of the Commonwealth Scientific and Industrial Research Organization (CSIRO) and Southern Australian Perpetual Forests (SAPFOR), indicate that this problem may well be overcome by selecting a legume with a very different pattern of water use from that of the pine. The introduction of legumes has produced large increases in early growth without affecting survival (Nethercott, pers. comm)[4/]. To date, these studies have concentrated on establishing legumes and pines together on second-rotation sites that have been windrowed and burned. It is planned to extend this work to sites where the logging residue has been crushed/macerated and to also utilize the considerable potential of these residues to supply N and conserve soil water.

Nitrogen supplied from litter and logging residue remaining after clearfelling.--The radiata pine plantations established at Rennick in southwest Victoria have provided an ideal opportunity to fully implement the principles elucidated by research and expressed by Flinn et al. (1980) that "retention of litter and logging residue to conserve organic matter, soil moisture and site nutrients, is likely to be the only reliable means by which site productivity of infertile sands low in organic matter can be maintained."

Radiata pine plantations were first established at Rennick in 1947, and in recent years many of the earlier plantings have been harvested and re-established. Operational trials reported by Farrell et al. (1981) indicated that a variety of mechanical methods could be used successfully to treat the logging residue from these relatively young, unthinned stands that contained no advanced regeneration. The most effective method employs a Roller-Chopper which flattens and chops the woody material into a mixture of sizes to produce a mulch over a relatively undisturbed soil. The mulch combined with a relatively intact litter layer inhibits the development of natural regeneration. The full re-establishment sequence following the clearfelling of about 40-ha compartments is:

1. Clearfelling should be completed by early summer so that residues are dry and brittle for maceration in late autumn-early winter. The absence of green slash at planting is also important to control the population of *Hylastes ater* (Paykull), an insect that lives in green slash and has the potential to kill large numbers of young seedlings (Harris, pers. comm.)[5/].

4/ Nethercott, K. H. Assistant Chief Forester, Southern Australian Perpetual Forests (SAPFOR).

5/ Harris, J. A. Research Officer, Entomology, Forests Commission, Victoria, Australia.

2. The residue of the heavily branched edge-tree represents a fire hazard, especially as it cannot be macerated successfully. For this reason, and to facilitate planting, this material, which covers about 5 percent of the total area, is windrowed soon after clearfelling and burned at the earliest safe opportunity.

3. The remaining residue, presently about 140 t ha^{-1} due to a depressed demand for small material, is macerated toward the end of autumn. The combined cost of (2) and (3) is about \$100 ha^{-1}, which is approximately equal to that of windrow burning.

4. In mid-winter, 1-year-old seedlings are hand planted at an approximate spacing of 2.4 x 2.4 m, at a cost of about \$120 ha^{-1}.

5. A weed control treatment is applied 6 weeks after planting, before the pines have commenced shoot growth. A mixture of amitrole (0.5-kg ha^{-1} a.i.) and atrazine (5-kg ha^{-1} a.i.) is applied over the pines in a strip that extends about 0.6 m on either side of the planting line. The cost is approximately \$60 ha^{-1}.

6. Natural regeneration is hand pulled about 12 months after planting at a cost of about \$50 ha^{-1}.

The total re-establishment cost is approximately \$330 ha^{-1}.

Two major problems have been encountered in applying the above sequence where the first rotation stand has been multithinned, as is commonly the case in neighboring areas in South Australia. First, due to a depressed pulpwood market the heavily branched crowns and large fractured logs must remain on site, and this material cannot be macerated successfully using the present Roller-Chopper. However, this problem may be resolved using machinery currently being evaluated. The "Hydro-ax", a 100-HP., articulated, four-wheeled, rotary slasher, is particularly promising, and in tests (Thomson, pers. comm)6/ has successfully reduced heavy slash at cost of about \$75 ha^{-1}.

The second problem concerns natural regeneration. The Hydro-ax efficiently removes advanced regeneration taller than 30 cm, but smaller plants often survive in large quantities and in addition to those that develop from seed after clearfelling, must be removed by other means. One promising approach is the use of a low-intensity fire prior to the final felling. Trials (Thomson, pers. comm.)6/ indicate that such fires can generate sufficient radiant heat to kill advance regeneration leaving the nutrient-rich litter layer virtually intact. This method, however, is unlikely to be better than 50 percent effective, and further treatment after clearfelling and maceration will be required (e.g., aerial spraying with amitrole, perhaps at rates as high as 5-10 kg ha^{-1} a.i.). It may be necessary to delay these treatments for several months until most of the seed has germinated and the protection (shielding) of seedlings by slash has diminished.

The influence of the Roller-Chopper sequence on early growth can be gauged quite accurately from an experiment established in 1975 to compare the growth of first and second rotation stands of radiata pine at Rennick (Squire et al. 1979). The experiment encompasses a range of site qualities and includes comparisons of first and second rotation growth on precisely the same sites and an examination of growth on matched first and second rotation sites. Stem analysis techniques were used to determine total underbark volume and height growth as functions of age before the first rotation stands were clearfelled. The second crop was established by hand planting into the unburned residue of the first crop. The plants used were raised from seed collected from the sites before clearfelling, and past practices were followed both in the nursery and for establishment and tending in the field.

The first statistical comparison of growth data between first and second rotation crops on the same site was made at age 5 years. Comparisons of mean predominant height (mean height of the 75 tallest trees ha^{-1}, Lewis et al. 1976) indicated that second rotation growth had not declined, and in fact had increased on the low-quality sites (Farrell et al. 1981). (There is evidence from Squire et al. (1979) and Farrell et al. (1981) that these responses might arise largely from increases in the availability of both water and nitrogen.) Further analysis (Squire, Farrell, and Flinn, unpublished data)7/ has confirmed that these responses are also true of volume growth. The improvement was again greatest on the low site qualities, where total volume underbark averaged about 30 m^3 ha^{-1} measured on the matched first rotation sites. Detailed methods and results will be presented elsewhere.

EXPECTATIONS

This discussion will concentrate on radiata pine growing on the infertile sandy soils in the southeast of South Australia and neighboring areas in Victoria.

Efforts to maintain/improve the productivity of these sites have concentrated largely on the early growth phase; that is, the first 4 to 5

6/ Thomson, D. S. Former District Officer, Rennick, Forests Commission, Victoria, Australia.

7/ Data on file at Southwest Research Centre, Victorian School of Forestry, Creswick, Victoria, Australia.

years after planting. Although improvements in early growth have been achieved from a variety of practices, in each case, they appear to be largely due to increases in both the availability of water (weed control and/or mulching) and nitrogen (inputs from either fertilizer, fixation by legumes, or from accelerated mineralization of organic N in logging residue).

The advantage in early growth given by the above treatments should be maintained if they are to increase productivity substantially over a full rotation (35 to 40 years). For this to occur, growth factors (e.g., light, water, nutrients, and CO_2) should be maintained at non-limiting levels. The nutrient requirement of P. radiata can be satisfied early in the rotation by nutrient inputs, and following canopy closure, largely by nutrient redistribution within the biomass (Madgwick et al. 1977). It can be assumed that light and CO_2 will not be limiting, and therefore, water availability remains as the critical factor that might limit plantation productivity.

On the shallow soils (< 2 m to limestone substratum), which have been planted extensively in this region, water availability may prevent the full maintenance of the early growth advantages described above. On the poorer sites studied at Rennick (Farrell et al. 1981, Squire et al. 1979), where the limestone substratum occurs at 1.8-2.0 m, the root zone appears to be fully occupied at canopy closure when available water reserves are virtually depleted by late summer-early autumn. This point was reached by about age 5 years on mulched sites (Farrell, Squire and Flinn, unpublished data)[8/], and is likely to occur 2 to 3 years later on untreated sites. To this stage (7 to 8 years after planting), increases in growth may be due largely to increased uptake of both nutrients (especially N, Squire et al. 1979) and water. Beyond this stage, further increases in growth due to treatment might only arise from more efficient use of the same limited supply of water, that is from increased water-use efficiency (unit of dry matter formed per unit of water transpired). Expectations of substantial gains productivity might depend largely on the extent to which water-use efficiency is influenced by nutrition, and especially by N-nutrition. This argument is also likely to be true of the extensive areas of radiata pine grown on shallow soils under water limited conditions elsewhere in southern Australia.

There is no published information for P. radiata on the influence of fertilizing on water-use efficiency, and differing results have been obtained with other conifers. Bradbury and Malcolm (1977) showed that potassium fertilizer reduced stomatal conductance to water vapor, and thus increased water-use efficiency in Sitka spruce (Picea sitchensis (Bong.) Carr.) seedlings, whereas van den Driessche (1973) working with slash pine (Pinus elliottii (Engelmn.)) found that although N fertilizer reduced transpiration, it also reduced net photosynthesis and so had little influence on water-use efficiency. I have examined effects of soil water and N treatments on water-use efficiency of P. radiata seedlings using pot studies (milligram dry matter per gram H_2O) and gas exchange techniques (micromole CO_2 per millimole H_2O). The pertinent findings are summarized below. Detailed methods and results, and an expanded discussion will be presented elsewhere.

In the pot studies, water-use efficiency generally increased when either the water supply was reduced or the N supply increased. When water was non-limiting, maximum water-use efficiency (2.9)[9/] was within the range that would be expected for plants such as P. radiata which use the C-3 pathway type of photosynthesis (Fischer and Turner 1978). This value was for fertilized plants (foliar N, 23.7 g kg^{-1}), was 38 percent higher than that achieved by unfertilized plants (foliar N, 11.8 g kg^{-1}), and was associated with a 2.5-times increase in dry matter production. The advantage due to N fertilizer was not sustained, however, once soil matric potential (ψ_m) was allowed to fall below about -0.07 mPa. In the field, where ψ_m is below -0.07 MPa for extended periods each year (Farrell et al. 1981), increases in water-use efficiency due to N fertilizer might therefore be somewhat less than the 38 percent achieved in this pot experiment.

The gas exchange studies showed that although N fertilizing resulted in greatly increased photosynthetic production, it also substantially increased transpiration. These responses underline the dilemma of land plants (Raschke 1976): "assimilation of CO_2 from the atmosphere requires intensive gas exchange; the prevention of excessive water loss demands that gas exchange be kept low." Therefore, although N fertilizing increased net photosynthesis from 1.26 µmol $m^{-2}s^{-1}$ for fertilized plants (foliar N, 24.1 g kg^{-1}), at the same vapor pressure difference (transpiration is a function of stomatal aperture and vapor pressure difference), it had little

8/ Data on file at Research Laboratory, Forests Commission Victoria, Treasury Place, Melbourne, Victoria, Australia.

9/ Comparisons of rainfall records with estimates of biomass accumulation and partitioning (from sources detailed by Squire and Flinn 1981) for radiata pine stands on shallow soils in this region suggest that this value (2.9 mg dry matter per g H_2O) could also be of the right order for field-grown plants. For a 40-year rotation, a mean annual consumption of about 5800 t H_2O ha^{-1}, equivalent to about 74 percent of the average annual rainfall, would be required to achieve a m.a.i. (stemwood) of about 23 m^3ha^{-1}, which is close to the average value for shallow soils in this region.

effect on water-use efficiency. This contrasts somewhat with the result obtained for well-watered plants in the glasshouse, where water-use efficiency was calculated as milligram dry matter per gram H_2O transpired. The most likely explanation for this difference is that respiratory losses at night and from roots were reduced by N fertilizer, a possibility supported by the much smaller root:shoot ratio for fertilized than for unfertilized plants.

I conclude from these pot studies and gas exchange experiments that under field conditions where soil water availability is likely to be limiting for extended periods each year, N fertilizing is unlikely to result in substantial improvements in water-use efficiency. This hypothesis needs to be tested under field conditions, where gas exchange characteristics, particularly as influenced by canopy structure, may be quite different.

Under the above hypothesis, a particular establishment practice would be expected to increase productivity over the rotation more or less in direct proportion to the increase it induces in water consumption by the pine crop (dry matter production = water consumption x water-use efficiency). On the shallow sands in this region it appears likely that any increased water consumption, and hence wood production, would be largely established within 5 to 8 years of planting (fig. 1). The previously described practice involving retention of logging residue, which has given a five- to six-fold increase in volume growth to age 5 years, might give only a modest increase of about 2 $m^3 ha^{-1}$ m.a.i. over a 35- to 40-year rotation. On the other hand, the early results do suggest that this practice will at least maintain productivity in the second rotation at the level of the first rotation, a proposition which will be tested using existing, well-advanced studies (Squire 1979).

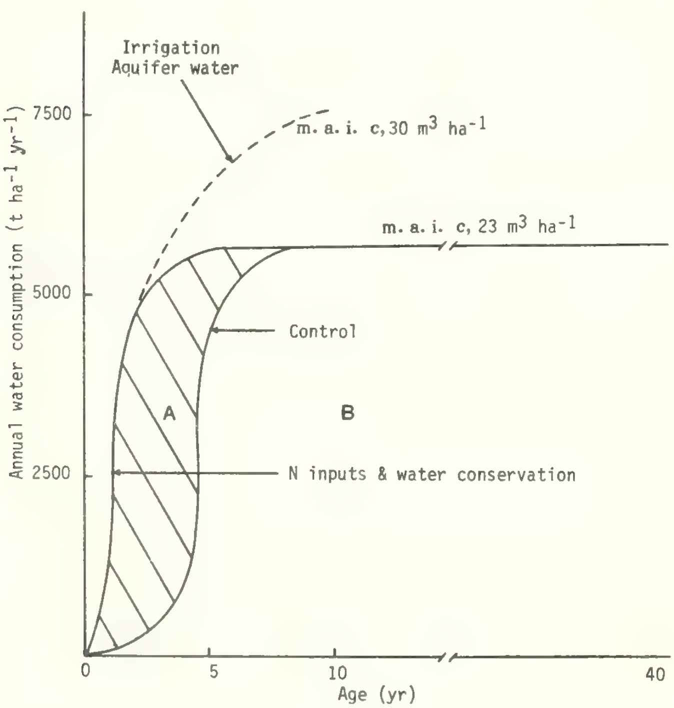

Figure 1.--An hypothesised pattern of water consumption for a P. radiata plantation showing the effect of improved establishment practice. For constant water-use efficiency, percentage increase in dry matter production over the rotation $= \frac{A}{B} \times 100$

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DECOMPOSING LITTER AS A SOURCE OF NUTRIENTS FOR SECOND-ROTATION STANDS OF SITKA SPRUCE ESTABLISHED ON PEATY GLEY SOILS

D. C. Malcolm and B. D. Titus

ABSTRACT: After clearfelling 40-year-old Sitka spruce stands on peaty gley soils in upland Britain a rise in the water table restricts the roots of second-rotation spruce transplants to the organic horizons (LFH) formed by the previous stand. The adventitious roots formed by the transplants are then dependent on the decomposition of the LFH for their nutrient supply.

The rate of decomposition of the LFH horizons is being followed by zero-tension lysimetry in a series of plots 0, 2, and 5 years after clearfelling. Leachates are analyzed at 3-week intervals for total and soluble N, NH_4-N and NO_3-N, P, K, Na, Ca and Mg. Results to date show some immobolization of N and P, loss of almost all K by year 5 and complementary reduction in dry weight of the former LFH. The implications for management are discussed.

INTRODUCTION

Almost 40 percent of afforestation in upland Britain has taken place on peaty gley (Histic Cryaquept) soils (Pyatt and Craven 1979). This soil type, with up to about 30 cm of organic matter has developed postglacially over tills of low permeability. Plantations of Norway spruce (Picea abies (L.) Karst.) and Sitka spruce (Picea sitchensis (Bong.) Carr.) were successfully established in the 1930s and 1940s by planting on raised and inverted turfs but these stands become susceptible to windthrow when they reach a top height of about 15 m. Low hydraulic conductivity of the peat (Boggie & Knight 1980) and the pore-sized distribution of the mineral horizons make drainage impractical, and the high winter water table restricts roots to the depth of the peat layer.

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When felling these stands before they are windblown, the trees are dropped in bands, leaving the accumulated brash (felling residues) in strips across the site to give heavy extraction machinery sufficient traction on the wet soils.

The felling removes the interception and transpiration of the canopy and results in a rapid rise of the water table to about 10-15 cm from the surface throughout the year (Malcolm 1979). The root systems of transplants inserted below this level generally die, and survival is dependent on placing the plant close to the old stumps, where the litter layer is deeper, and on the production of adventitious roots. Second-rotation plants therefore must rely initially for

Table 1--Stand and site data of experimental plots in 1981

Plot	Age at felling	Yield[1] class	Stand density Stems	Stand density Basal area	LFH depth brash strip	LFH depth clear strip	Peat depth brash strip	Peat depth clear strip
	(yrs)		(stems ha^{-1})	(m^2 ha^{-1})	- - - - - - - - - -cm-	- - - - - - - - - -		
T, mature stand	-	10-12	4250	63.0		6.7 $\pm$0.9[2]		26.0 $\pm$2.1
0, felled 1/81	42	10-12	4150	47.8	8.4 $\pm$1.2	7.3 $\pm$0.8	17.3 $\pm$1.3	18.3 $\pm$2.3
2, felled 12/79	40	10-12	3550	65.6	7.5 $\pm$0.9	5.7 $\pm$0.4	14.2 $\pm$1.1	16.3 $\pm$1.4
2 (NPK) felled 12/79	40	10-12	3590	61.4	8.5 $\pm$0.7	6.4 $\pm$0.8	23.7 $\pm$2.2	21.7 $\pm$2.4
5 felled 1/76	40	10	4030	47.0	5.8 $\pm$0.7	5.3 $\pm$0.6	28.0 $\pm$1.77	27.7 $\pm$1.2

1/ Maximum mean annual increment (m^3 ha^{-1} y^{-1}) (Hamilton and Christie 1971)

2/ 95 percent confidence limits

their water and nutrients on the decomposing litter layers, the LFH (Kubiena 1953) of the previous stand. For management reasons replanting is often delayed for 2 or more years after felling, so it is important to know the rate at which nutrients may be released from the old litter layers. Only a sparse ground flora reinvades these peaty gley sites during this period.

This paper describes an experiment in progress that estimates the release of nutrients available to replanted trees from the litter layer of the previous stand.

METHODS

Experimental Design

A series of five 0.1-ha plots were selected in January 1981 on typical peaty gley soils (Pyatt 1970) at an altitude of about 300 m in Keildee Forest, Northumberland, United Kingdom (table 1). The plots were located in areas which had been clearfelled 0, 2, and 5 years previously and on which the brash from the previous crop had been banded. On the 2-year site, two plots were established, one of which had received a NPK treatment (160 kg N, 50 kg P, 100 kg K per hectare) in June 1981 as part of a Forestry Commission fertilization experiment. A fifth plot was established in a mature stand of Sitka spruce as a control.

The input of litter (branches and needles) from the fellings was assessed for dry weight and nutrient content. Nutrient release from the LFH was estimated by zero-tension lysimetry and the nutrient capital in the rootable volume was determined from soil samples.

Nutrient Input on Clearfelling

Plot 0 was surveyed immediately after felling, and the strips of brash were sampled at random with 1-m-wide transects taken at right angles through the strip. Four fractions (>2.5-cm, 1-2.5-cm, and <1.0-cm live branches and dead branches) were sorted and weighed in the field. Subsamples were dried at 105°C in the laboratory, the needles separated, weighed, and ground for later analysis. Precipitation was collected in plastic funnel rain gauges (23-cm diameter).

Zero-Tension Lysimetry

Lysimeters of 881-cm^2 surface area were constructed from polystyrene trays (23.5 x 37.5 x 5.5 cm) with an outlet on the bottom at one end. Excised LFH horizons were placed in the lysimeters and supported on a 0.5-cm nylon mesh laid over a supporting grid of plastic. Leachate passing through the lysimeters drained freely to 25-liter collection vessels that had light excluded to discourage algal growth.

In each felled plot, 10 lysimeters were installed in both brash and clear strips for a total of 80 lysimeters. The lysimeters were placed as close to randomly selected stumps as possible (i.e., the replanting position), by cutting out the LFH horizons, placing them in the trays and inserting the lysimeters so that the surfaces of the LFH horizons in and outside the trays were level. The sides of the trays protruded by about 2 mm above the surrounding surface to prevent surface flow.

Leachate volumes were measured at 3-week intervals and samples taken to determine concentra-

tions of NH_4-N, NO_3-N, dissolved organic N, P, K, Ca, Mg, Na, and pH in the laboratory. Lysimeter and collection vessel size are able to accommodate the maximum anticipated rainfall (250 mm) in a 3-week period. On a few occasions in winter the system froze preventing collection and periods of low precipitation also led to longer intervals between collections.

Soil Samples

To assess the nutrient capital in the potential rooting zone of each plot, 15 randomly located cores (5-cm-square section) of the organic horizons were taken from both brash and clear strips. The corer used (Cuttle and Malcolm 1979) causes no compaction in organic deposits allowing an accurate assessment of bulk density. The cores were air dried after division into LFH, peat, and upper mineral horizons. Subsamples were then oven dried at 95°C, digested, and analyzed for total nutrient content.

Laboratory Analysis

Leachate and rainfall samples were normally analyzed within 2 days of collection; but when this was not possible, they were stored in the dark at <5°C. During this time no changes in solution chemistry were found. Automated colorimetric methods were used to determine concentrations of NH_4-N (Crooke and Simpson 1971, Fraser and Russell 1969) NO_3-N (Allen 1974, Henrikson and Selmer-Olsen 1970), and PO_4 (Murphy and Riley 1962); K and Na were determined by flame emission, and Ca and Mg by atomic absorption spectrometry after addition of La.

RESULTS

Because this study is in progress and not all the statistical analyses have been completed, the results given here are provisional.

Litter Input at Clearfelling

The weights of the different size fractions added to the soil at clearfelling were estimated from the brash strips in plot 0 and are given in table 2. The strips averaged 8 m wide and were separated by 4-m bands clear of brash.

Table 2--Dry weight of litter fractions at clearfelling

Diameter size class (cm)	kg ha^{-1}	(95 % conf. limits)
Live branches >2.5	13 465	(±2979)
Live branches 1.0 - 2.5	3 641	(± 805)
Live branches <1.0	7 241	(±2946)
Live needles	9 324	(±3435)
Dead branches	14 799	(±1967)
Total	48 470	(±9647)

Site Nutrient Capital

The adventitious roots of second rotation transplants develop in the LFH horizons of the peaty gley soil. The nutrient sources available to these roots are therefore confined to that horizon with the addition of the fine litter fraction left after clearfelling. The combined weights of these materials were estimated from the 15 soil cores per treatment plot and are given in table 3 with their mean nutrient concentrations and the total per site.

There is no apparent difference in the weight of the LFH horizons of the mature stand or of the clear bands between brash strips of the clearfelled 0- and 2-year plots, but the value for the 5-year site is considerably less at 48 t ha^{-1}. Aggregating the brash into strips shows an increment of 12-13 t ha^{-1} added to the LFH (mainly needles and some fine twigs) in the early years but this difference is not found in plot 5. The samples that the data in table 3 are based on were taken some 6 months after plot 2 (NPK) was fertilized. The data show that there has been some increase in the concentration of P and K, but the urea -N applied is not in evidence. The N concentration of both brash and clear strips in plots 2, 2(NPK), and 5 appear greater than those of plots T and 0, but because of the lower LFH weight on plot 5, the total on site is considerably less.

The original peaty layer overlying the gley may become available to tree roots after canopy closure restores the interception and transpiration processes to the water balance on these sites. The nutrient store in this material is considerably greater than that in the LFH horizons but does not show the same trends.

The values for the peat (table 4) are approximately one order of magnitude greater than those for the LFH horizons (table 3), but because the N and P are organically bound and decomposition rates are low (Williams 1974), only a proportion of these elements may become available for uptake by the planted trees.

Nutrient Release in Leachates

The concentration of NH_4-N in the leachate varies markedly over the period (fig. 1a) with a tendency to attain its highest levels in late summer. The concentrations also appear to increase with time from clearfelling, which may indicate a delay in the release of this ion.

The reason for the inversion of the concentrations from the brash and clear strips in NO_3-N release (fig. 1b) is unknown, but the main physical difference between these two locations is the increased surface temperatures in the clear strips. On a sunny day in summer the LFH surface reaches temperatures in excess of 30°C, especially near the old stumps (W. Harper, pers. comm.[1/]). Concentrations peak in summer, and the

[1/] W. Harper. Data on file. University of Edinburgh, Edinburgh, United Kingdom.

Table 3--Dry weight, nutrient concentrations, and contents of LFH horizon after clearfelling

Plot	Dry wt.	Concentration N	Concentration P	Concentration K	Total nutrient content N	Total nutrient content P	Total nutrient content K
	($t\ ha^{-1}$)	($mg\ g^{-1}$)			($kg\ ha^{-1}$)		
T	65.7	11.9	0.63	0.82	774	41.3	53
	(± 9)[1/]	(±0.5)	(±0.03)	(±0.06)	(±91)	(±4.9)	(±6.7)
0 clear	81.1	11.6	0.67	1.13	942	54.7	92
	(±11)	(±0.4)	(±0.04)	(±0.16)	(±152)	(±10.2)	(±17)
brash	84.2	10.6	0.55	0.99	905	46.9	82
	(±9)	(±0.4)	(±0.05)	(±0.11)	(±113)	(±7.5)	(±10)
2 clear	66.8	13.2	0.61	0.71	873	40.4	51
	(±9)	(±0.8)	(±0.05)	(±0.14)	(±112)	(±6.0)	(±19)
brash	78.6	13.5	0.72	0.90	1059	57.2	70
	(±10)	(±0.9)	(±0.04)	(±0.05)	(±141)	(±8.8)	(±9)
2 (NPK) clear	73.6	12.6	0.82	1.23	935	65.3	96
	(±12)	(±0.5)	(±0.21)	(±0.29)	(±165)	(±25.8)	(±35)
brash	86.6	13.2	1.02	0.95	1157	86.5	83
	(±10)	(±0.8)	(±0.16)	(±0.12)	(±175)	(±12.2)	(±15)
5 clear	48.8	12.6	0.56	0.67	617	27.4	32
	(±4.5)	(±0.6)	(±0.04)	(±0.07)	(±63)	(±2.9)	(±4)
brash	47.9	14.8	0.68	0.65	706	31.7	31
	(±7.4)	(±0.9)	(±0.05)	(±0.08)	(±113)	(±4.3)	(±5)

1/ (±95 % conf. limits; n = 15)

Table 4--Dry weights, nutrient concentrations, and content of the peat layer of peaty gley soils

Plot	Dry wt.	Concentration N	Concentration P	Concentration K	Total nutrient content N	Total nutrient content P	Total nutrient content K
	($t\ ha^{-1}$)	($mg\ g^{-1}$)			($kg\ ha^{-1}$)		
T	522	16.2	1.11	3.34	8222	569	1816
	(±61)[1/]	(±1.7)	(±0.11)	(±0.49)	(±872)	(±71)	(±408)
0 clear	331	18.0	1.37	1.87	5640	443	685
	(±69)	(±1.8)	(±0.14)	(±0.32)	(±756)	(±75)	(±285)
brash	303	17.9	1.43	2.32	5280	429	728
	(±36)	(±1.8)	(±0.13)	(±0.39)	(±529)	(±49)	(±163)
2 clear	362	16.8	1.14	1.71	5979	407	636
	(±34)	(±1.3)	(±0.08)	(±0.37)	(±506)	(±38)	(±156)
brash	342	16.3	1.21	1.96	5458	411	708
	(±43)	(±1.8)	(±0.12)	(±0.36)	(±671)	(±57)	(±225)
2 (NPK) clear	408	17.2	1.10	1.25	6969	447	521
	(±38)	(±0.6)	(±0.05)	(±0.21)	(±618)	(±42)	(±119)
brash	432	18.6	1.22	1.67	7910	525	769
	(±58)	(±0.8)	(±0.09)	(±0.38)	(±936)	(±78)	(±257)
5 clear	440	20.4	1.06	1.10	8896	462	509
	(±31)	(±1.2)	(±0.07)	(±0.33)	(±546)	(±19)	(±188)
brash	470	20.2	1.08	1.40	9147	483	782
	(±71)	(±1.5)	(±0.09)	(±0.48)	(±511)	(±24)	(±497)

1/ (±95 % conference limits; n = 15)

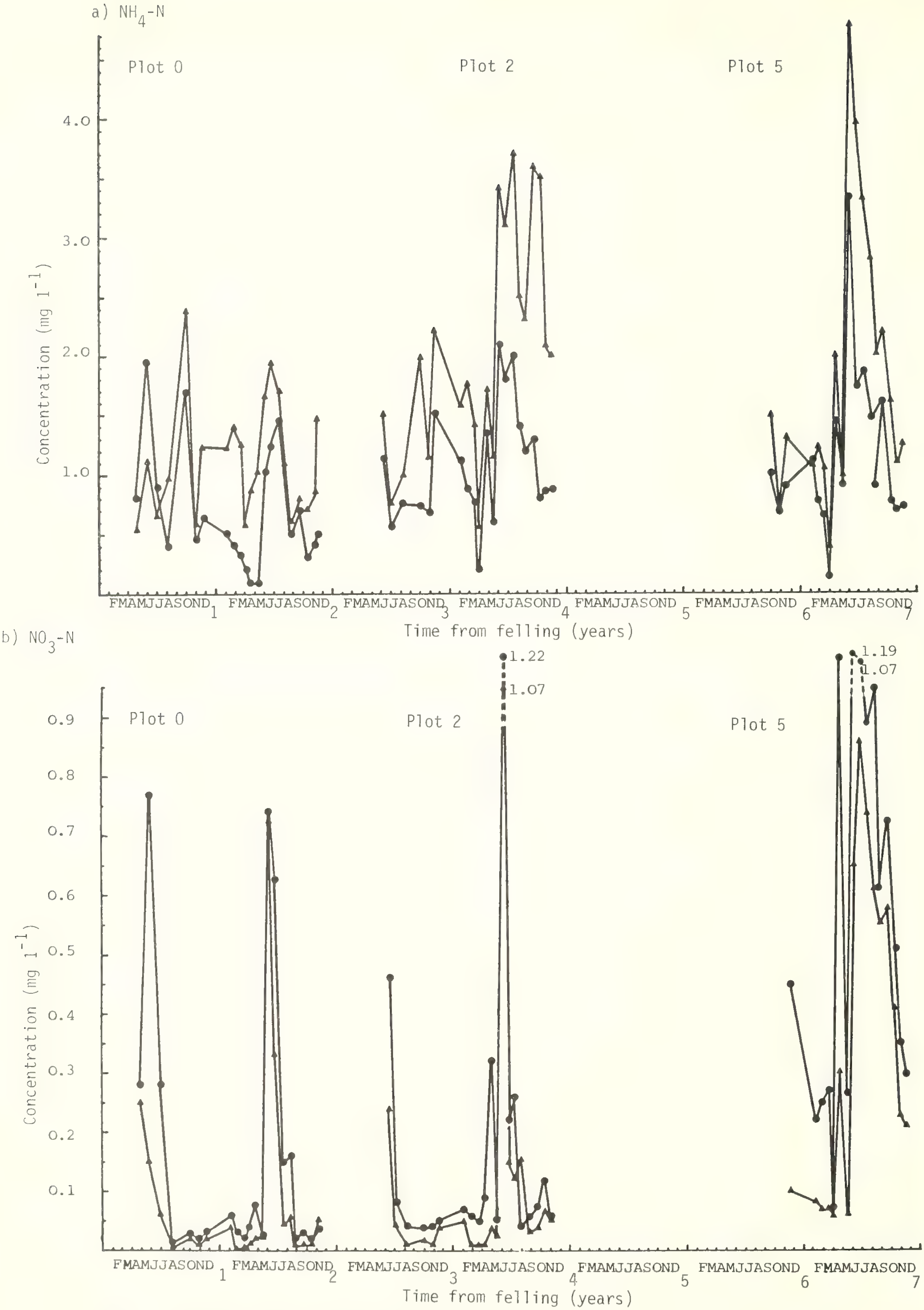

Figure 1.--Mean concentrations in lysimeter leachates April 1981 - Nov. 1982.
a) Ammonium nitrogen, b) Nitrate nitrogen
(Leachates from brash strips - ▲ and clear strips ●)

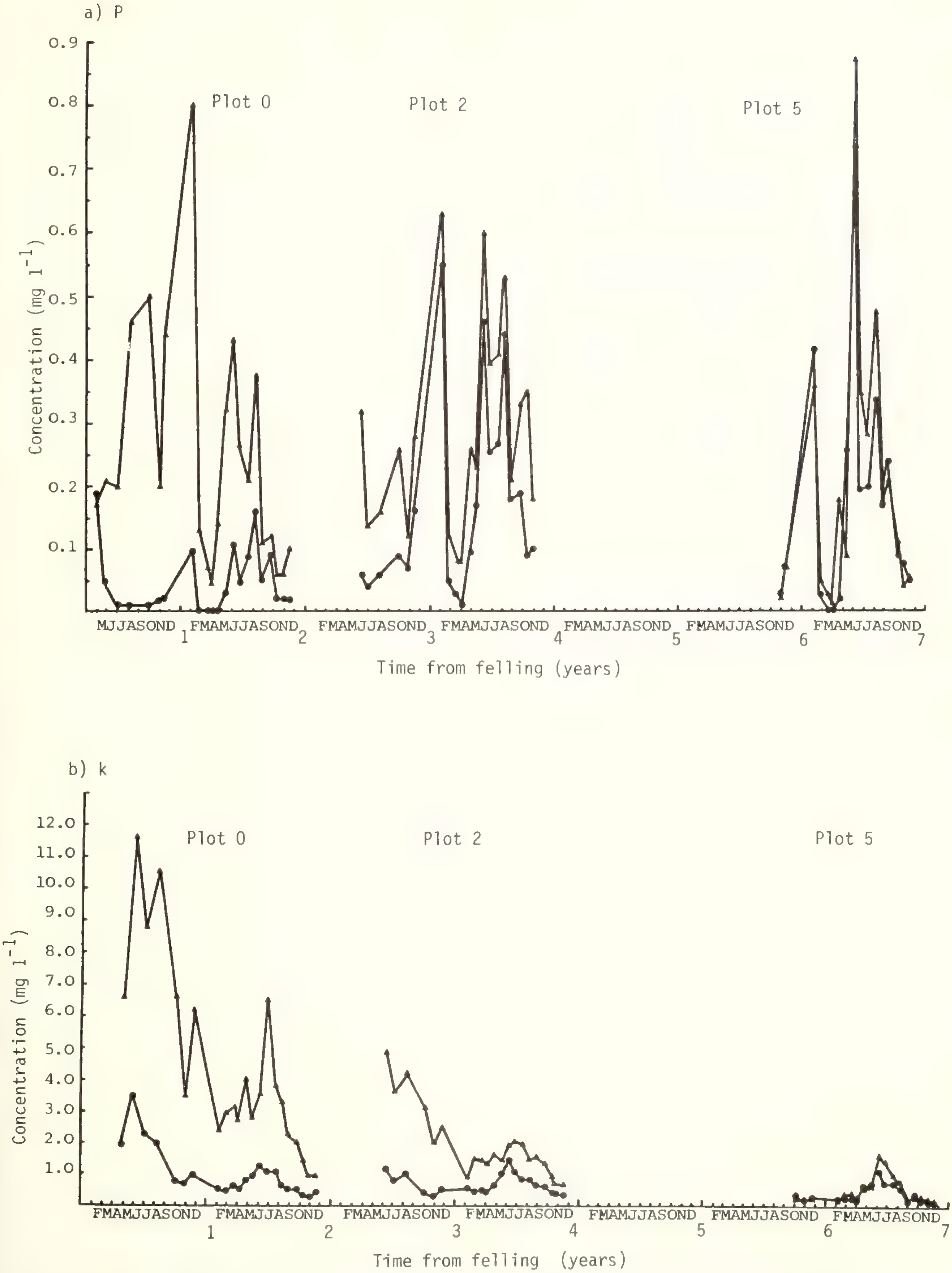

Figure 2.--Mean concentrations in lysimeter leachates April 1981 - Nov. 1982. a) Phosphorus, b) Potassium . (Leachates from brash strips - ▲ and clear strips - ●).

highest levels are found in the oldest clearfelled area--plot 5. NO_3-N concentrations, however, are generally less than 20 percent of those for NH_4-N.

In the early years following felling, the effect of creating brash strips shows up strongly in the P concentration of leachates (fig. 2a), but after 5 years the differences have largely gone. The general level of concentrations from the brash strip declines over the period, but those from the clear strips tend to increase after 4 years, suggesting early immobilization.

After 5 years (plot 5), the concentration of K in the leachates from brash strips has fallen to about that in the precipitation. The leachates from the clear strips attained these levels within 1 year.

Following fertilization of the 2-year-old site (2 NPK) there were large increases in concentrations of NH_4-N, P and K in the leachates. Collections made shortly after fertilizer application had concentrations of 42 mg L^{-1} NH_4-N, 6.5 mg L^{-1} P, and 40 mg L^{-1} K. Twelve months later the concentrations were still 9 mg L^{-1} NH_4-N, 2.5 mg L^{-1} P, and 10 mg L^{-1} K--all considerably higher than in untreated plots. The pH of the leachates from plot 2 (NPK) increased by about one unit to 4.5-5.0 after treatment with no increase in NO_3-N release.

DISCUSSION AND CONCLUSIONS

A feature of these peaty gley sites is the slow invasion of vegetation after clearfelling. Even after 5 years there is no sward developing on the clear strips where only isolated, but quite vigorous, individual plants typical of the wet acid conditions have become established (e.g., _Calluna vulgaris_, _Eriophorum vaginatum_, _Juncus squarrosus_, and _Erica tetralix_). These probably derive from the soil seed bank. On the brash strips, however, quite extensive patches of _Chamaeneirion angustifolium_ occur but seem unable to extend on to the areas devoid of brash. This distribution of the vegetation highlights the differences in the microclimate and nutritional status of the clear and brash strips. The evidence from the lysimeters is that the aggregated brash is releasing much higher concentrations of nutrients than the cleared strips. The difference between brash and cleared strips appears to diminish by the 5th year, however, as shown by both the total nutrient and leachate data (table 3, figs. 1 and 2).

On many site types the loss of nutrients after clearfelling is transient and ceases as soon as the site is revegetated or naturally regenerated with trees. On these peaty gleys, however, it is possible that quite a large fraction of the nutrients released from the decomposing litter may be lost in runoff from the site before sufficient root growth can develop to take up these nutrients. This possibility is enhanced by the continually high water table in the poorly conducting peaty layer; much of the annual precipitation (about 1 400 mm) runs off immediately below the LFH horizons.

The high water table and anaerobic conditions near the surface make replanting or regenerating these sites difficult. If transplants have their nursery root systems immersed in the anaerobic layers they die, but if planted shallowly they can dry out in the frequent spring droughts. In addition, the system of brash aggregation in strips to assist movement of extraction vehicles makes replanting the strips difficult and expensive. It is common practice, therefore, to allow at least 2 years to elapse before attempting to restock the area by which time the brash is more amenable to planting. The results from this study suggest that the delay may mean permanent loss of nutrients, although the tendency for immobilization of N and P may reduce this. The problem would seem to be greatest for the K supply unless atmospheric input is sufficient to maintain the replanted trees. In first-rotation stands on these sites, K-deficiency symptoms in the lower crown are observable after canopy closure, especially where rooting is confined to the peaty layer. As K apparently is lost so quickly from the litter of the previous stands (fig. 2b), the availability of this nutrient may be a problem in second-rotation stands.

The aggregation of litter and hence nutrients in the brash bands might be expected to have an effect on replanted trees analogous to the "ash-bed effect" noted in Australasia following windrowing and burning of brash (Bunn and Will 1973). These effects have not yet been seen, possibly because of the poor stocking achieved in the brash strips.

Although most of the nutrient concentrations found in lysimeter leachates are low, any trees able to form adventitious roots at the base of the LFH horizons will receive a continual supply of LFH leachate flowing downslope over the relatively impermeable peat. Whether this supply is adequate to maintain growth rates appropriate to the climatic conditions will be shown from the fertilization experiments in progress. The main problems may appear in the late-thicket stage when the stands make maximum demands on the site and the old LFH horizon will have largely decomposed. The availability of the nutrients stored in the peaty layer will then be crucial.

In a study of long-term processes using a chronosequence of sites, it is important to ensure as far as possible that the successively sampled sites are comparable. In this case, the sites were located on extensive areas of peaty gley soils that had developed a relatively uniform topography. The soils show little variability in profile characteristics (table 4), and this study has concentrated on the decomposition of the superficial horizons. The main sources of variation therefore lie in the amount and quality of the litter deposited on the surface, both throughout the first rotation, and at

clearfelling. The similarity of the stands before clearfelling in age, productivity, and density (table 1) indicated that the variation between the sites could be accepted. Without a replicated series it is not possible to be certain that the changes over time (for example in LFH dry weight) do not arise from variation in the original stands. The rates of nutrient release and litter decomposition, derived from the replicated lysimeters, are unlikely to vary much between sites and, therefore, can provide a valid estimate of the nutrients becoming available to newly planted trees in the 7 years after clearfelling.

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PHYSICAL CHANGES TO SANDY SOILS PLANTED TO RADIATA PINE

R. Sands

ABSTRACT: Soil strength and soil water availability are important soil physical factors in determining the productivity of Pinus radiata D. Don plantations on sandy soils in southern Australia. A simple mechanistic model for predicting root growth as a function of soil strength, soil water potential, and root mechanical properties is developed. The maintenance of desirable physical properties in these soils is shown to depend strongly on the maintenance of organic matter.

INTRODUCTION

The decline of site productivity in forests is usually considered in terms of loss in chemical fertility; i.e., loss of available nutrients in the root zone at critical times for growth. Soil physical factors can also be important, though, and may interact with chemical factors in productivity decline. One reason why physical factors are sometimes ignored is that a productivity problem can often be partly or wholly overcome by fertilization. Yet it should not be assumed under these circumstances that the problem is solely nutritional. Any adverse factor in the soil environment that reduces root length may induce nutrient deficiency in its own right. This component of nutrient deficiency can be removed by correcting the non-nutritional factor that reduces root length. Thus under some circumstances the addition of fertilizer can mask an underlying primary problem, and this could be serious in the long term.

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Non-nutritional soil factors that reduc length are disease, salinity, poor ae adverse soil temperatures, high soil st and reduced water availability to roots. discuss in this paper the last two factor strength and soil water availabil important soil physical factors to cons site productivity. I shall discuss the particular reference to the maintenance productivity for monocultures of radiat growing on orthic podzols (Dudal 1970) from dune sands such as occur in western V and the southeast of South Australia. conclude from these discussions that th important single factor in the lo maintenance of productivity on these sc maintenance of soil organic matter. opinion, no management practice that redu amount of soil organic matter or restric distribution with depth in these soils sh considered, even at the expense of sho gains.

SOIL STRENGTH

Root Growth

Root elongation is a turgor pressure-m response. A simple model for root elo

without mechanical constraint from the soil can be written:

$$e = (\Psi_p - \Psi_{pt})f, \quad \text{for } \Psi_p > \Psi_{pt} \tag{1}$$

where e is the cell elongation rate, Ψ_p is turgor pressure, Ψ_{pt} is the threshold turgor pressure below which elongation ceases, and f is the degree of softening of the cell walls with units of fluidity. If roots are growing in soil with pores of lesser diameter than the roots, then the soil will exert a restraining pressure, P_s, which will act against turgor pressure in cell elongation. Thus a possible model for root growth in soil is:

$$e = (\Psi_p - \Psi_{pt} - P_s)f, \quad \text{for } \Psi_p > (\Psi_{pt} + P_s) \tag{2}$$

$$= (\Psi - \Psi_\pi - \Psi_{pt} - P_s)f, \quad \text{for } \Psi\pi < (\Psi + \Psi_{pt} + P_s) \tag{3}$$

where Ψ and Ψ_π are total and osmotic water potentials of the elongating cells. P_s is difficult to measure in soils. A reasonable approximation can be measured in medium-textured soils with a finely tapered metal penetrometer of semi-angle α (Farrell and Greacen 1966). Using the penetrometer, P_s can be obtained:

$$P_s = q\ (1 + \tan\phi \cot\alpha) \tag{4}$$

where q is soil strength measured as penetrometer resistance and ϕ is the angle of soil metal friction. Combining equations (3) and (4) gives

$$e = [\Psi - \Psi_\pi - \Psi_{pt} - q(1 + \tan\phi \cot\alpha)]f. \tag{5}$$

The rate of root elongation will decrease as root water potential (Ψ) decreases or soil strength (q) increases. Root water potential will decrease as soil water potential (Ψ_s) decreases or as evaporative demand increases on plants in soils of low hydraulic conductivity. Soil strength increases as Ψ_s decreases and as soil bulk density increases. This means that in drying soil, root elongation may be reduced by the increasing water stress and increasing soil strength acting together. This reduction in root elongation can be counteracted to some extent by osmoregulation (decrease in Ψ_π), by lowering of threshold turgor (decrease in Ψ_{pt}), and by hormone-mediated cell wall softening (increase in f). Greacen and Oh (1972) found pea radicles osmoregulated with 100 percent efficiency against a moderate decrease in Ψ_s but at only 70 percent efficiency against increased P_s. Under these circumstances decreased root growth in drying soil was caused by increased soil strength and not water stress. When soil strength is increased by compaction (increased soil bulk density), air-filled porosity may be reduced to the point where root growth is inhibited by poor aeration. Increased soil strength and poor aeration may therefore act together to reduce root growth under certain circumstances.

Root elongation rate or root frequency in soil typically decreases exponentially with soil strength as shown for radiata pine in figure 1. This figure shows there is very little root growth at penetrometer resistances over 3 000 kPa. Increased soil strength can also

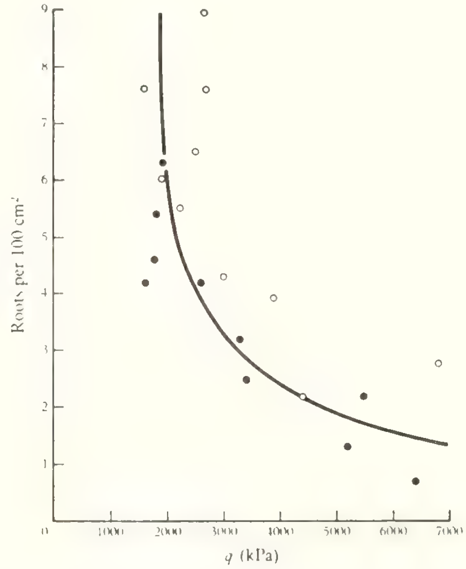

Figure 1.--The relationship between frequency of roots (no. per 100cm^2) of radiata pine and soil strength q (kPa) of Mt. Burr sand (o) and Young sand (●). (q was measured as resistance to a penetrometer.) (From Greacen and Sands 1980.)

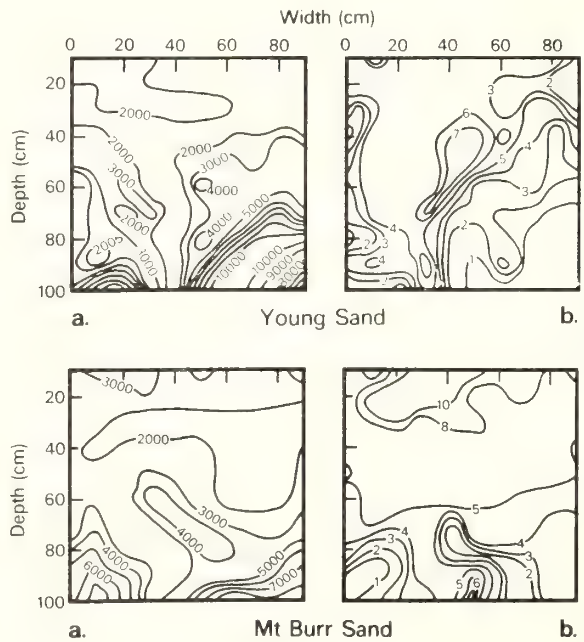

Figure 2.--(a) Isobars of penetrometer resistance for Young sand and for Mt. Burr sand (the shaded area represents critical q>3 000 kPa); and (b) root frequency (roots per 100cm^2) on pit face (shaded area represents a frequency <0.04cm^{-2}). (From Sands et al. 1979.)

Table 1--Root configuration data from radiata pine seedlings grown in soil at different mean bulk densities (from Sands and Bowen 1978)

Criterion	Soil bulk density 1.60		1.48		1.35
	(g cm^{-3})				
Main axis					
Mean length (cm)	14.4	**	47.0	NS	54.3
Diameter 1cm from apex (mm)	2.30	**	1.37	*	0.81
First-order laterals					
Number	89.6	*	68.1	NS	60.5
Mean length (cm)	7.1	**	14.3	**	21.4
Distance from apex (cm)	0.53	NS	0.89	NS	1.06
Total length (cm)	636	*	974	*	1295
Frequency on main axis (cm^{-1})	6.22	**	1.45	*	1.11
Diameter 1cm from apex (mm)	1.19	NS	1.07	*	0.86
Second-order laterals					
Frequency on first-order lateral (cm^{-1})	1.06	NS	0.82	*	1.65
Mean length (cm)	0.94	NS	1.15	NS	0.97

NS Not significant
* $P<0.05$
** $P<0.01$

Levels of significance refer to adjacent treatments.

affect root configuration. For example, Sands and Bowen (1978) found that reduction in root length of radiata pine (Pinus radiata D. Don) following compaction was compensated for, to some extent, by an absolute increase in the number of first-order laterals (table 1). Spatial variability in strength in a soil profile can be quite large. Under these circumstances roots seek out the pathways of least resistance to penetration as demonstrated for radiata pine in figure 2. Even if a soil contains a large proportion of high-strength material, there may be sufficient low-strength soil to allow adequate root growth. Soil strength could restrict root growth in a dry year but not in a wet year. Also a restricted root system may be adequate in fertile soils but not in infertile soils. Productivity loss caused by increased soil strength following compaction is difficult to measure because of spatial variability in soil strength and because soil strength interacts with so many other factors that affect root growth and uptake of water and nutrients. One approach is to develop a model, and some progress has been made on a model for radiata pine growing on sandy soils that takes these interacting factors into account.

Soil Compaction

The soils discussed here were derived from dune sands and have lower bulk densities in the undisturbed condition than when they are remolded following disturbance. The reason for this is obscure, but it means the soils are easily compacted by forces originating within and external to the soil, particularly shear forces, and that such compaction is largely irreversible through natural recovery processes (Sands et al. 1979). Differences in soil strength profiles can be seen among alternate land uses and presumably reflect differences in degree of site disturbance among these land uses. This is demonstrated in figure 3 which compares soil strength profiles with depth for undisturbed native forest, pasture, and first and second rotation radiata pine where these land uses occur adjacent to each other on the same soil type. The results are

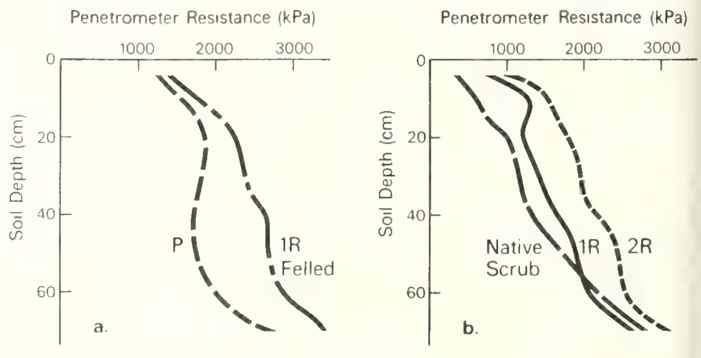

Figure 3.--Changes in penetrometer resistance with soil depth for different land uses adjacent on the same soil type: (a) P = pasture, 1R-felled = after felling first rotation 49-year-old radiata pine; (b) Native scrub = native Eucalyptus baxteri and E. huberiana forest, 1R = first rotation 70-year-old radiata pine, 2R = second rotation 12-year-old radiata pine following first rotation 46-year-old pine.

representative of many further comparisons not reported here. The soils under native forest are least compacted and under pine plantations most compacted, and often soils under second rotation pines are more compact than under first rotation pines. In other words, soils are compacted in the process of growing radiata pine on these soils, and soil compaction may increase with subsequent rotations of radiata pine.

A probable main cause for compaction on these soils under radiata pine is from man-made forces on the soil associated with clearing, planting, tending, thinning, clearfelling, and log removal from the forest. The proportion of soil surface area involved in this complex of operations can be quite large. Certainly logging equipment is known to compact these soils (fig. 4). Strategies for minimizing compaction on these soils during harvesting operations were outlined by Greacen and Sands (1980). Of prime importance is avoiding machines that generate large shear forces and avoiding logging on soils low in organic matter or that are very wet. The sensitivity of such soils to compaction is summarized by consolidometer tests shown in figure 5. These tests represent a realistic field situation and are summarized in detail in Sands et al. (1979). This is the first clue about the importance of organic matter in these soils--soils low in organic matter are more easily compacted. If organic matter in the soil is lost from the profile over time, soils may be compacted by their own weight in the absence of disturbance.

SOIL WATER AVAILABILITY

The soils discussed here are duplex with a sandy A horizon overlying a clay B horizon. The A horizon, however, is often over 1 m deep and sometimes several meters deep and, as most root activity in radiata pine is confined to the surface 50cm, only the physical properties of the sandy A horizon will be discussed here. The major factor determining the physical properties of these sandy soils is soil organic matter content, and the results are therefore presented as a function of soil organic matter content (measured as percent loss on ignition).

Figure 6 shows the soil water characteristic curve and corresponding soil hydraulic conductivity of A horizon sand with 1.2 percent soil organic matter. This soil behaves as a typical coarse-textured medium with low soil water retention and low unsaturated hydraulic conductivity. These relationships change with soil organic matter content as shown in figure 7 and table 2. Water-filled porosity (equivalent to volumetric water content) increases with soil organic matter at both field capacity (-10 kPa soil matric potential) and wilting point (-1 500 kPa soil matric potential). Available water (i.e., water held between field capacity and wilting point) increases (linearly) four times over the range 0-3 percent soil organic matter (fig. 7). Increasing organic matter

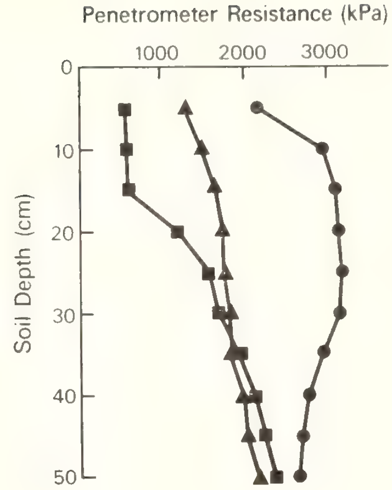

Figure 4.--Changes in soil strength q (kPa) with depth (cm) of Mt. Burr sand on a logging road (●), after 10 passes with a JD 740 rubber-tired skidder pulling full-length logs of radiata pine (▲), and adjacent undisturbed soil (■). (Each point was the mean of six observations, and q was measured as resistance to a penetrometer.) Greacen and Sands (1980).

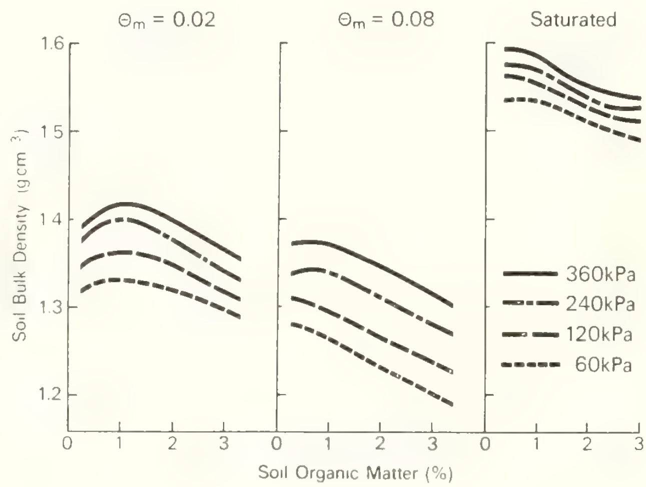

Figure 5.--Consolidometer tests showing how soil bulk density changes under different loads on Mt. Burr sand at different soil organic matter contents and different gravimetric water contents (θ_m).

increases the number of fine pores, and the physical properties of the coarse soil approach that of a medium-textured soil. Increase in bulk density has the same effect, but the increase in available water so obtained is small compared to that when soil organic matter is increased (fig. 7).

Saturated hydraulic conductivity increases as soil organic matter and soil bulk density

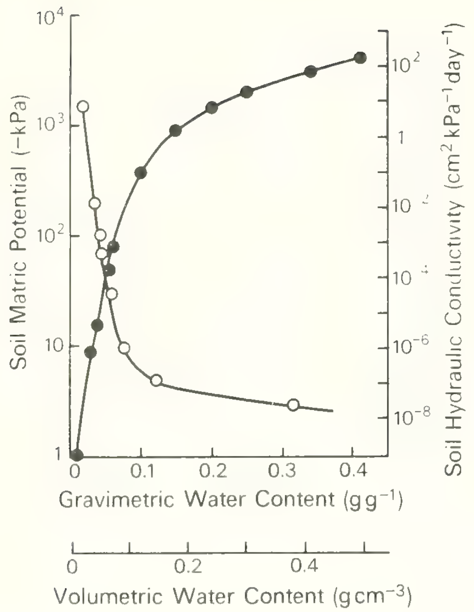

Figure 6.--The moisture characteristic (o) and hydraulic conductivity function (●) of Mt. Burr sand. Sands and Theodorou (1978).

decreases (table 2). Unsaturated hydraulic conductivity, however, is greatly decreased in unsaturated soils. Unsaturated hydraulic conductivity is decreased three times at field capacity and 10^6 times at wilting point as soil organic matter decreases from 2.46 to .012 percent. Under these circumstances the resistance to water flow from soil to roots would be large compared with resistance in the plant (Sands and Theodorou 1978).

Total porosity decreases with soil organic matter content and soil bulk density increase (fig. 8). At 3.0 percent soil organic matter content and a bulk density of 1.6 cm^{-3}, water-filled porosity is greatest (fig. 7), total porosity least (fig. 8), and air-filled porosity (14 percent) derived by difference is also least. Root growth should not be limited by poor aeration at an air-filled porosity of 14 percent (Sands et al. 1979). Restricted root growth following compaction of these soils is probably due to mechanical impedance of root growth by the soil and not by poor aeration.

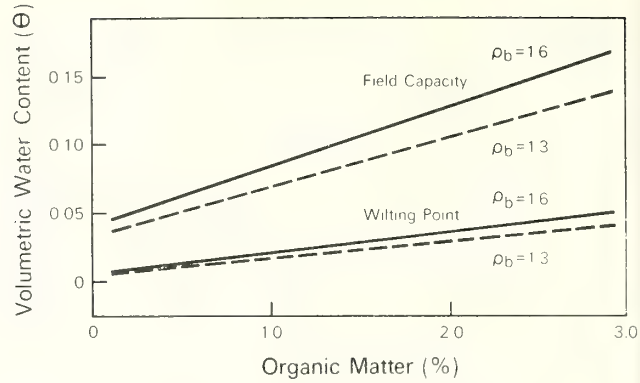

Figure 7.--Change in water-filled porosity with soil organic matter content at field capacity (-10 kPa matric potential) and wilting point (-1 500 kPa matric potential) at soil bulk densities (ρ_b) of 1.3 and 1.6 g cm^{-3}.

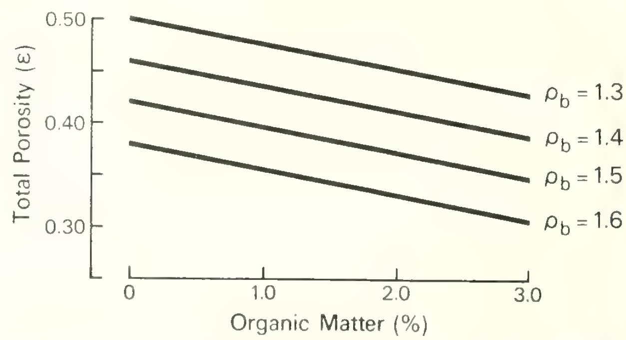

Figure 8.--Change in total porosity with soil organic matter content over a range in soil bulk densities (ρ_b, g cm^{-3}).

Table 2--The effect of organic matter (OM) and bulk density (ρ_b) on the saturated hydraulic conductivity (K_o) and unsaturated hydraulic conductivities (K_{-10kPa}, $K_{-1\ 500\ kPa}$) of Mt. Burr sand at -10 and -1 500 kPa matric potentials (from Sands et al. 1979)

OM	ρ_b	K_o	K_{-10kPa}	$K_{-1\ 500kPa}$
(% loss on ignition)	(g cm^{-3})	- - - - - - - - - - - -	(cm hr^{-1})	- - - - - - - - - - - - -
0.012	1.4	157 ± 10[1/]	2.5×10^{-3}	2.5×10^{-14}
	1.5	87 ± 10	3.5×10^{-3}	2.5×10^{-13}
0.97	1.4	43 ± 3	2.2×10^{-3}	10^{-10}
	1.5	24 ± 2	4×10^{-3}	3.5×10^{-9}
2.46	1.4	16 ± 0.8	8.5×10^{-3}	8×10^{-8}
	1.5	10 ± 0.3	9.5×10^{-3}	8×10^{-8}

1/Standard errors of the mean for K_o are based on five observations.

Table 3--Change in soil organic matter, total nitrogen, available phosphorus and potassium, and cation exchange capacity with soil depth under second rotation 24-year-old radiata pine that had naturally regenerated or that had been planted after a fierce broadcast burn

	Organic matter	Total N	Available P1/	Available K	Cation exchange capacity2/
	(%)	(%)	($\mu g\ g^{-1}$)	($\mu g\ g^{-1}$)	(Cg^{-1})
Natural regeneration3/					
0- 5cm	3.54/	.074	5.2	49	8.3
5-10	2.3	.045	2.6	76	7.1
10-20	1.5	.026	1.0	40	4.3
20-40	.5	.007	3.8	236	-
40-60	.3	.004	3.1	309	-
Burned and planted					
0- 5cm	2.1	.038	3	81	6.5
5-10	1.5	.029	2	91	5.0
10-20	1.0	.021	1.4	96	2.9
20-40	.8	.011	2.2	146	-
40-60	.6	.006	1.8	129	-

1/Available P was measured by a modified Olsen technique (Colwell 1965).
2/Cation exchange capacity was determined as by Tucker (1974).
3/The natural regeneration and burned areas were adjacent to each other on the same soil type.
4/Each figure the mean of five samples where standard error was 20 percent or less of the mean.

SOIL ORGANIC MATTER

The importance of soil organic matter in these sandy soils has been emphasized by Sands et al. (1979), Flinn et al. (1980), and Farrell et al. (1981). The A horizons of these soils contain negligible clay, and desirable chemical properties of these soils are vested in the organic matter. Organic matter is an important nutrient source in its own right. Figure 9 shows the relationship between soil total nitrogen and soil organic matter on unfertilized soils over a wide range in soil depths, tree ages, and nitrogen management regimes. The line represents a constant C:N ratio of 38. The high C:N ratio suggests there is a significant component of undecomposed plant residue in the soil organic matter. Table 3 shows soil organic matter, total nitrogen, available phosphorus and potassium, and cation exchange capacity of soils under 24-year-old radiata pine that had either naturally regenerated or had been planted following a fierce broadcast burn on the site. These treatments were adjacent to each other on the same soil type. At 24 years after the burn, there was considerably less soil organic matter on the burned site with corresponding smaller values of total nitrogen, available phosphorus, and cation exchange capacity. Available potassium increased on the burned site as expected. This is one representative example of several such comparisons. More detailed information on burning litter between rotations on these soils is given by Flinn et al. (1979) and Woods (1980). Cation exchange capacities are low in these soils, and there is a linear relationship between cation exchange capacity and soil organic matter (fig. 10). Added fertilizer elements will therefore be more easily leached from soils low in organic matter.

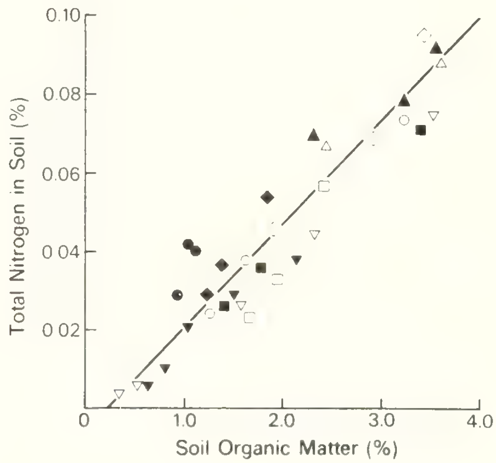

Figure 9.--The relationship between soil organic matter content and total soil nitrogen. All sites are for radiata pine growing on orthic podzols in the Mt. Gambier region of South Australia. Twenty-six-year-old trees on adjacent sites with (●) and without (○) 17-year fallow; 24-year-old trees on adjacent sites that were naturally regenerated (▽) or planted following fierce broadcast burn (▼); 10-year-old trees on adjacent sites that were (▲) or were not (△) planted to legumes; and trees aged 7 (◆), 20 (◇), 35 (□), and 50 (■) years growing on site quality 2 (Lewis et al. 1976). Data obtained from a range of soil depths between 0 and 100 cm. The line represents a constant C:N ratio of 38.

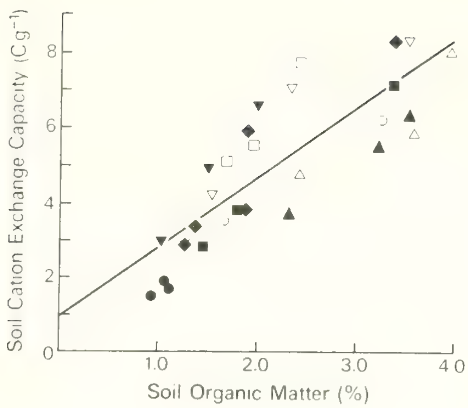

Figure 10.--The relationship between soil organic matter and cation exchange capacity (Tucker 1974). Symbols are the same as in figure 9.

As demonstrated previously, desirable physical properties of these soils are also vested in soil organic matter. If the soils lose organic matter, they will compact more, will hold less water available to tree roots, and will present a large resistance to the flow of water through soils to roots.

CONCLUSIONS

Maintenance of productivity on these sandy soils depends primarily on maintenance of soil organic matter, and any management procedure that removes present or future soil organic matter or restricts its distribution with soil depth is suspect, even if it produces good short-term gains. By contrast, any management procedure that improves soil organic matter status should improve productivity on these sites in the long term.

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WATER SEEPAGE AND WATER BALANCE IN FOREST SOILS AND RELATIONS TO WATER UPTAKE BY TREES IN THE FIELD

Felix Richard

ABSTRACT: Water flow and balances were investigated in a one-dimensional flow study under a single Douglas-fir tree and a two-dimensional flow study under a stand of silver fir and spruce. The one-dimensional study showed deep seepage during the winter to average 1 mm day^{-1} which was 10 to 15 times for the same process during summer. During a period of regular rainfall in the summer when the available water remained close to field capacity evapotranspiration was optimal at 3 mm day^{-1}. During a dry period when matrix potentials reached >800 cm, evapotranspiration was reduced to 1.02 mm day^{-1}.

The two-dimensional flow study showed that during dry periods of no rainfall evapotranspiration strongly influences hydraulic gradients, but during wet periods (10 mm rainfall day^{-1}) water flow is predominantly determined by gravity heads.

INTRODUCTION

On a worldwide basis, water and nutrition are dominant growing factors for plants.

For a more intensive knowledge of physical and chemical productivity of plant-producing soils, investigations on water movements and water balances in forest and agricultural soils in their natural locations are necessary.

In the laboratories of soil physics, Federal Institute of Technology (ETHZ), in Zurich, Switzerland, investigations on water flow and water balances in soils are major research subjects.

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We are presenting data from two projects: (1) a one-dimensional flow study in a forest soil (Typic Hapludalf) as influenced by root activity, climatic conditions, and time, and (2) a two-dimensional flow study in unsaturated forest soils (Typic Distrocrept) on a slope.

Both projects were investigated on the Ph.D. level. Leader of the first project was Dr. Franz Borer, Dipl.Ing. ETHZ, and of the second project Dr. Peter Greminger, Dipl.Ing. ETHZ.

ONE-DIMENSIONAL FLOW STUDY

A one-dimensional flow experiment (Borer 1982) was established in the rooting zone (530 m^3 of soil volume) of a dominant Douglas-fir (Pseudotsuga menziesii). This tree is part of a mixed forest stand situated in the Swiss lowlands. Mean annual rainfall (1975/76) was 968 mm, mean temperature 9.8° C, and length of the vegetation period is approximately 210 days.

Five hundred tensiometers were installed in the rooting zone, each representing approximately 1 m^3 of soil.

Hydrodynamically the rooting zone was considered to be an open system and the roots a sink. Input and output of water (rainfall and seepage, respectively) were calculated with Darcy's law and water balance with Richard's flow-equation.

The highest monthly and annual evapotranspiration of this Douglas-fir amounts to 5 mm d^{-1} (1976, May, August) and 3.4 mm d^{-1} (1976) respectively. During the vegetation period deep seepage was calculated to 0.11 mm d^{-1}; i.e., a very small amount. This value corresponds to a water loss of 23 mm (1975) for the total vegetation period (210 days). During winter (155 days 1975/76), deep seepage averaged 1 mm d^{-1}, which is 10 to 15 times the amount for the same process during summer. From April 20 to November 8 (1976, 210 days), 70-80 percent of the rainfall that fell on the canopy was taken up by the Douglas-fir tree.

Of special interest was the water budget in a period with no rain; i.e., from June 3 to July 8, 1976 (34 days), we called it "dry period," as opposed to a "wet period (June 2 to July 7, 1975).

"Dry period" refers to the 34 days of no rain within the vegetation period (fig. 1). The water content in the rooting zone decreased from 36.91 percent$_v$ to 34.15 percent$_v$, and matrix potential increased from <150 cm to >300 cm. Consequently deep seepage became very small (0.06 mm d^{-1}). The lateral flux into the rooting zone was neglectibly small (0.13 → 0.04 mm d^{-1}). Towards the end of this dry period, the highest values of matrix potentials were reached at >800 cm and evapotranspiration (ET) decreased to 1.02 mm d^{-1}; i.e., matrix potentials of this magnitude reduced (ET) significantly to 50 percent of that at "field capacity" with a matrix potential of 60 cm.

"Wet period" refers to the 36 days of regular rainfall with approximately no change in water content (37 percent$_v$) in the rooting zone (fig. 2). This water content maintained matrix potentials between 87 and 133 cm. The amount of available water remained close to field capacity, which corresponds to a tension of 80 cm (assuming a normally drained soil). Water uptake by trees was optimal. The evapotranspiration rate amounts to 3 mm d^{-1}, which is almost the same amount as rainfall (3.1 mm d^{-1}).

Tentatively Borer (1982) tried to calculate biomass increment as a function of water balance in the rooting zone using equation (1).

$$\text{Biomass increment} = \frac{\Sigma\ ET \cdot A \cdot \int_{H_2O}}{CT \cdot \int_{dry\ wood} \cdot 10^3} \qquad (1)$$

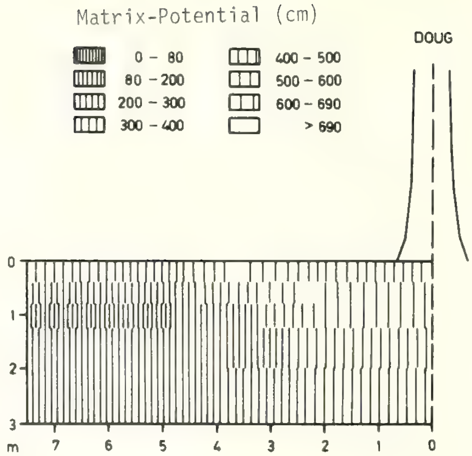

Figure 1.--A cross sectional profile of the soil water matrix potential under a Douglas-fir tree on July 9, 1976 during the "dry period."

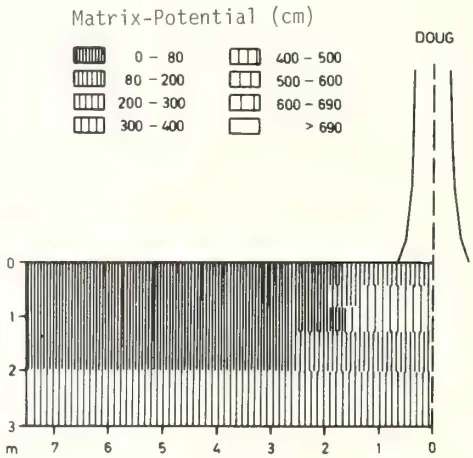

Figure 2.--A cross sectional profile of the soil water matrix potential under a Douglas-fir tree on June 20, 1976 during the "wet period."

Water uptake by Douglas-fir was hydrodynamically considered, as mentioned, as a sink. The boundary conditions were as follows: ET = 501 $dm^3\ m^{-2}$ (calculated), area (A) investigated = 176 m^2, coefficient of transpiration (CT) = 400 kg kg^{-1} (estimated), density of wood (dry) $\int_{dry} = 0.47$ kg dm^{-3}, density of water $\int_{H_2O} = 0.99$ kg dm^{-3}. From the amount of water taken up by roots, 0.25 percent was fixed in drymass of wood, whereas 99.75 percent was transpired.

Using equation (1), we obtain an annual increment of 16 $m^3\ ha^{-1}$ (mass of wood: approximately 60 percent of total biomass).

TWO-DIMENSIONAL FLOW STUDY

In 1976/77, a two-dimensional water flow field experiment (Greminger 1982) was installed 610 m above sea level. The forest soil was a Typic Distrocrept, on a 40-percent slope exposed to the north. The forest canopy was a 90-year-old stand of silver fir and spruce. Annual rainfall was 1 033 mm a^{-1} (1976) and 1 262 mm a^{-1} (1977) respectively. Temperature varied from -0.5° C (January) to 18° C (July).

In 1976 a <u>rainless</u> period ("dry period") between June 18 and July 9 was of special physical and hydrological interest (fig. 3). By evapotranspiration, water uptake by roots was extremely intensive. Hydraulic gradients changed directions; i.e., their values increased from soil surface down to deeper parts of the rooting zone. Water flowed from lower parts of the soil to the soil surface. A water divide occurred in the forest soil. The flow pattern (fig. 3) clearly shows how roots were distributed and where they extracted water out of the soil.

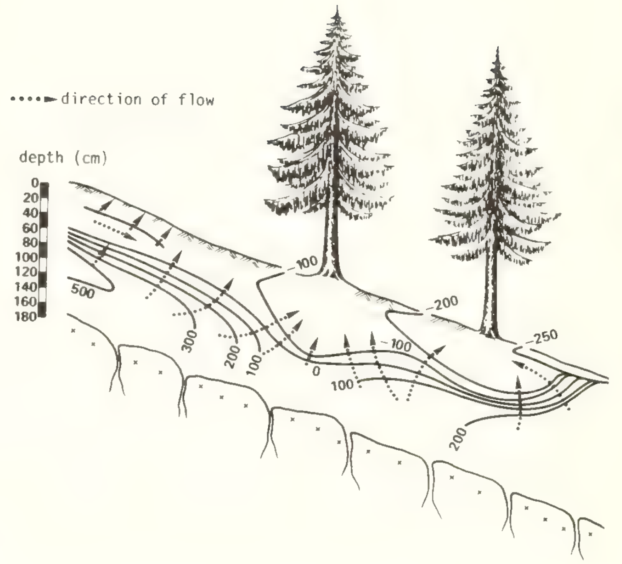

Figure 3.--Total water potential distribution (cm) after 36 days of no rain ("dry period," June/July 1976).

A completely different flow pattern ("wet period") is shown during rainy weather with 10 mm of rainfall per day. A situation like this is shown in figure 4 (June 4, 1976). Equipotential lines are almost horizontally oriented and their potentials are decreasing downslope. This drives the direction of water flow vertically from soil surface to greater soil depths.

Although evapotranspiration is also active under rainy weather conditions, no significant influence of evapotranspiration on the direction of equipotential lines was seen. Water flow is predominantly controlled by gravity heads.

We found that under normal weather conditions (i.e., no extreme dry periods with no rainfall for more than 10 days) our Douglas-fir takes 80 percent of transpiration water out from 0- to 40-cm soil depth, while only 20 percent is supplied from depth >40 cm.

We consider the soil investigated as a lysimeter with imaginary boundaries. Calculations of water balances gave the following data (Greminger 1982):

Period	Rain-fall	Deep seep-age	Lateral flow	Evapotrans-piration
	- - - - - - -	-	(mm) - - - - - - -	
May-Oct. 1976	560	207	172	519
Nov. 1976-April 1977 (excl. Feb. 1977)	352	421	178	75
May-Oct. 1977	496	182	164	483

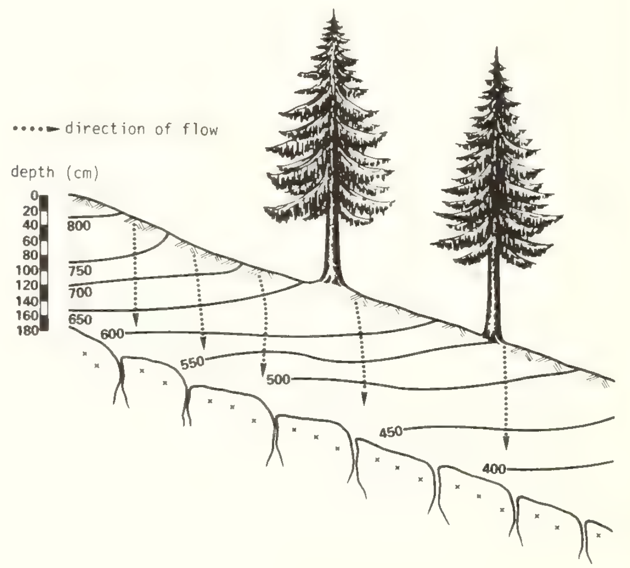

Figure 4.--Total water potential distribution (cm) during continuous rainfall of 10 mm day^{-1} ("wet period," May/June 1976).

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THE EFFECTS OF HARVESTING INTENSITY ON NUTRIENT DEPLETION IN FORESTS

Dale W. Johnson

ABSTRACT: The effect of harvesting on nutrient removal from a given site is relatively easy to evaluate. The amount of nutrient removed varies with amount of biomass harvested, species, and age. Broad generalization about any of these factors must be viewed with caution, however, because exceptions as well as unknowns may be significant.

The importance of nutrient removal by harvesting to nutrient status and productivity of the ecosystem is difficult to assess, because the availability of nutrients to trees will be determined by a number of unpredictable factors, including atmospheric inputs, soil weathering, leaching, and microbial mineralization-immobilization (the latter being especially important for N). Thus, while many investigators have, through a nutrient budget evaluation, forecast problems with supplies of Ca and few researchers forecast problems with supplies of N because of intensive harvesting, the effects of harvesting on the availability of nutrients to the regenerating forest remains unknown and constitutes a significant research need.

INTRODUCTION

Conceptually, the assessment of forest harvesting effects on nutrient depletion is simple. It can be done by determining nutrient removals in harvest, inputs from the atmosphere and soil weathering, and outputs via erosion and leaching. If projections indicate a decline in nutrient status, appropriate fertilizers must then be prescribed to preclude the development of nutrient deficiencies. In practice, of course, some of these processes are difficult to measure (i.e., soil weathering and N fixation), and for others (i.e., atmospheric inputs, erosion and leaching), long-term (i.e., rotation-length) information is lacking. Furthermore, effects of harvesting on mineralization-immobilization processes affecting N availability are difficult to predict. Only in the case of vegetation biomass and nutrient content are estimates relatively easy to obtain and therefore abundant. Information on the errors associated with such estimates is scarce, however. Nutrient removal in biomass is determined by estimating or measuring biomass and multiplying by nutrient concentrations in a representative sample of the biomass. Errors in biomass estimation can therefore be multiplied by sampling variation for nutrient concentrations and errors in nutrient analyses. Biomass and nutrient

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concentration are affected by a number of factors including age, species, position in the tree, climatic conditions, and soil nutrient status. It is not difficult to obtain reasonably good information on some of these factors (i.e., age, species and climatic conditions), but good quantitative information on other factors (i.e., position in tree and soil nutrient status) requires an intensity of sampling seldom feasible given the normal time and monetary constraints. Although it is relatively easy to estimate the effects of harvesting at varying intensities on nutrient removal from various sites, it is difficult to assess the accuracy of such estimates.

The actual effects of such removals on the nutrient status of the site depend upon a number of factors not easily estimated, however. To what extent might nutrient removals in harvesting be compensated for by atmospheric inputs (including N fixation) and soil weathering? To what extent are nutrient losses exacerbated by leaching and erosion over the next rotation? Can trees increase the efficiency of nutrient utilization when available supplies become low (e.g., Turner 1977) or, conversely, does current uptake and cycling of nonlimiting nutrients constitute "luxury consumption?" How might a change in species composition affect available nutrient supplies (e.g., by altering soil weathering rates) (Boyle and Voigt 1973)? How might harvesting at various intensities affect mineralization-immobilization processes, thus affecting soil N availability? These questions are fundamental to the overall goal of assessing harvesting effects on nutrient status, yet answers to them are seldom available. One major problem is that most of these questions are of a long-term nature (i.e., one or more rotations) whereas nutrient cycling information is usually of a short-term nature (exceptions being work with chronosequences to simulate stand development) (Turner 1981).

Nonetheless, various investigators, while fully aware of the limitations of the information available to them, have assessed the effects of intensive forest harvesting on forest nutrient status, and many of these investigators forecast the development of nutrient deficiencies not now observed (Alban et al. 1978, Baker 1978, Boyle and Ek 1972, Freedman et al. 1981, Johnson et al. 1982, Morrison and Foster 1979, Weetman and Webber 1972, Wells and Jorgensen 1979, White 1974). The theme of this paper [- "The effects of harvesting intensity on nutrient depletion in forests" -] parallels that of recent reviews (Kimmins 1977, Van Hook et al. 1982) and a symposium (Leaf 1979) devoted to the subject of intensive harvesting effects on forest nutrient status. Clearly, a full review of the literature would be prohibitively lengthy as well as redundant. Rather, it is the intent of this paper to consider some basic principles relevant to intensive harvesting and to examine the validity of many of the often-cited generalizations about harvesting effects on nutrient status.

EFFECT OF SPECIES

It is generally true that, for a given climatic region, deciduous trees contain more nutrients per unit biomass than coniferous trees (Marion 1979). It is incorrect, however, to conclude that this is always the case. For instance, the Picea abies (L.) Karst. stand at Solling, West Germany, contains less bole and total aboveground biomass than the Fagus sylvatica stand there, yet the Picea stand contains more P and Ca in bole tissues and more total aboveground N, P, K, and Ca than the Fagus stand (table 1). Thus, the Picea stand contains more nutrients per unit biomass than the Fagus stand. Similarly, the Picea mariana (Mill.) B.S.P. stand in Alaska contains only sightly more biomass but three to four times more Ca than the Betula papyrifera Marsh. stand there. On the other hand, the pine type at Walker Branch Watershed, Tennessee, has lower nutrient content than the yellow-poplar or oak-hickory types, although biomass values are similar (table 1).

Generalizations concerning nutrient content per unit biomass of coniferous vs deciduous species appear to have little meaning and may, in fact, be misleading. It may be possible, however, to generalize about individual species or even genus. Some investigators have noted high concentrations of Ca in bark and woody tissues of Quercus and Carya species, for example (Day and McGinty 1975, Johnson et al. 1982). Alban et al. (1978) noted large differences among three coniferous (Picea glauca (Moench) Voss, Pinus banksiana Lamb., and P. resinosa Ait) and two deciduous (Populus tremuloides Michx. and P. grandidentata Michx.) species in terms of aboveground nutrient accumulation. Aspen had very high Ca concentrations in bark, and spruce had very high Ca concentrations in foliage. These accumulations caused significant reductions in soil-exchangeable Ca in aspen and spruce stands as compared to those in adjacent red and jack pine stands.

Harvesting of various species in mixed stands can have a marked effect on the removal of some nutrients. For instance, harvesting only pines in a 30-year-old loblolly pine plantation at Walker Branch Watershed, Tennessee, would result in the removal of 85 of all bole biomass or 83 of total aboveground biomass (table 2). Harvesting only pines results in the removal of 70 to 80 of total aboveground N, P, and K. However, harvesting only pines removes merely 59 of aboveground Ca (because of low Ca concentrations in pine woody tissues as compared to those in many of the invading hardwood species). There would therefore be a 41 increase in Ca removal for a 15- to 17-increase in biomass yield if all trees, as opposed to pines only, were harvested in this plantation.

EFFECTS OF STAND AGE

The rate of nutrient and biomass accumulation in coniferous forests has been generally observed to be greater prior to crown closure than after

Table 1--Biomass, N, P, K, and Ca content of bole and total aboveground (foliage + branch + bole) trees at some coniferous and deciduous sites (data adapted from Cole and Rapp 1981)

Location	Species	Age	Bole content					Total aboveground content				
			Biomass	N	P	K	Ca	Biomass	N	P	K	Ca
		years	Mg.ha^{-1}	---------kg.ha^{-1}--------				Mg.ha^{-1}	---------kg.ha^{-1}---------			
Walker Branch, Tennessee, USA	Pine type	30-80	89	100	7	60	164	121	214	18	125	307
	Yellow-poplar type	30-80	83	135	8	90	307	109	267	21	172	537
	Oak-hickory type	30-80	90	171	9	114	498	122	369	24	220	856
Solling, West Germany	*Picea abies* (L.) Karst.	115	196	255	37	98	264	233	628	65	342	379
	Fagus sylvatica L.	122	238	368	5	206	215	274	581	20	273	303
Central Alaska	*Picea mariana* (Mill.) B.S.P.	130	86	95	14	52	391	113	215	29	76	625
	Betula papyrifera Marsh.	50	84	130	9	64	111	97	221	20	105	164

Table 2--Biomass and nutrient removals in bole-only vs. whole-tree harvests of pines only vs. all trees in a 30-year-old loblolly pine plantation on Walker Branch Watershed, Tennessee

	Biomass	N	P	K	Ca
	Mg.ha^{-1}	----------------kg.ha^{-1}--------------			
		Bole-only harvest			
Pines[1]	119(85%) ±8	123(77%) ±8	10(83%) ±0.6	73(79%) ±5	137(59%) ±9
All trees	140 ±7	159 ±10	12 ±1	92 ±6	233 ±30
		Whole-tree harvest[2]			
Pines[1]	151(83%) ±8	221(75%) ±12	19(73%) ±1	133(76%) ±7	224(59%) ±12
All trees	182 ±9	294 ±16	26 ±1.5	176 ±11	378 ±46

NOTE: Standard deviations of estimates among plots (n = 8) are given.

[1]Percent of total aboveground content in parentheses.

[2]Foliage + branch + bole.

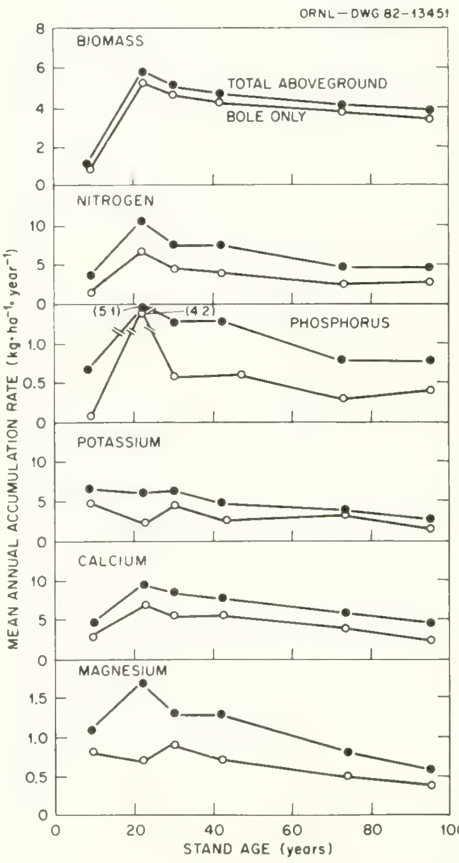

Figure 1.--Mean annual accumulation rates of biomass, N, P, K, Ca, and Mg in bole and total aboveground tree tissue of an age sequence of Douglas-fir stands (data adapted from Turner 1981).

crown closure (Miller 1981, Switzer and Nelson 1972, Turner 1981). This, coupled with the predominance of nutrient-rich biomass components (foliage and small woody tissue), causes short-rotation harvesting to place greater demands on site nutrient capital than longer-rotation harvesting (Hansen and Baker 1979, Miller et al. 1980, Wells and Jorgensen 1979). This is illustrated by the data for the Douglas-fir stand sequence studied by Turner (1981) (fig. 1). In this case, the mean annual accumulation rate (or stand content in kg/ha^{-1} divided by stand age in years) of biomass, N, P, Ca, and Mg in aboveground tree biomass peaked at about age 20 (when crown closure occurred) and declined thereafter. The rate of accumulation of K was highest in the earliest stage of development (age 9) and declined with age thereafter (fig. 1). The decline in the rate of nutrient accumulation was greater than the decline in the rate of biomass accumulation because of the increasing proportion of nutrient-poor large woody tissues in older stands. Thus, the

biomass yield per unit nutrient (Marion 1979) generally increased with stand age (fig. 2). Potassium was somewhat exceptional, however.

Stand development in uneven-aged and/or mixed-species forests is much more complex than in even-aged, monoculture forests such as in the Douglas-fir example, but information on nutrient accumulations for the former is lacking. Our studies of whole-tree harvesting in an uneven-aged, mixed deciduous species forest at Oak Ridge indicate that some patterns of nutrient accumulation with stand development may differ substantially from those observed in even-aged, coniferous forests. For instance, Ca concentrations in woody tissues of stump sprouts of oaks and hickories are actually lower than in mature bole tissue (table 3). For N, P, and K, stump sprouts have higher concentrations than mature bole tissue and for Liriodendron, stump sprouts have higher Ca concentrations as well (table 3). Thus, depending on species composition and biomass production, the rate of Ca accumulation per unit biomass may be greater in mature forests than in young forests at this site. Studies are now in progress to determine whether or not this is the case. In any event, it seems clear that the patterns documented for even-aged, monoculture coniferous forests cannot be safely extrapolated to uneven-aged and/or mixed-species forests. More research on nutrient cycling with stand development in mixed-species and uneven-aged forests is needed, specifically with regard to the effects of different age and species distribution on aboveground biomass and nutrient accumulation rates.

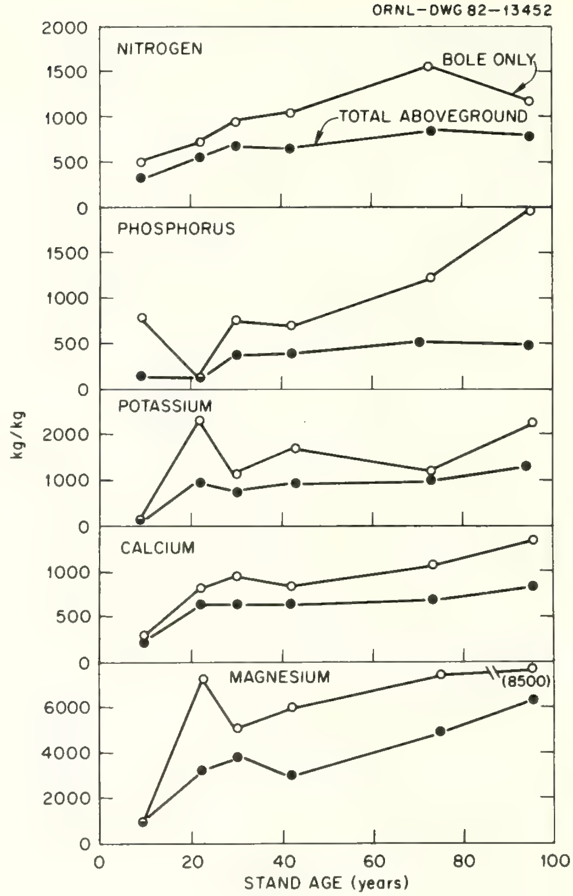

Figure 2.--Nutrient efficiency (kg biomass per kg nutrient content) of an age sequence of Douglas-fir stands (data adapted from Turner 1981).

EFFECTS OF HARVESTING VARIOUS BIOMASS COMPONENTS

In general, nutrient concentrations are greatest in foliage and small branches and least in large branch and bole tissue (Wells and Jorgensen 1979, Van Hook et al. 1982). Whole-tree harvesting therefore generally results in greater nutrient removal per unit biomass removal than does bole-only harvesting (Van Hook et al. 1982, Wells and Jorgensen 1979).

While this generalization is valid in most cases, there are exceptions. Some hardwoods, most notably Quercus and Carya, have rather high calcium concentrations in woody tissues (mostly in the bark) (Day and McGinty 1975, Johnson et al. 1982). Bole tissue, sampled as a proportional (pie-shaped or disk) composite of wood plus bark, often has Ca concentrations equal to or in excess of those in small branch or foliar tissue. An example of such a case is shown in figure 3 for Quercus prinus L. sampled during a whole-tree harvesting study at Oak Ridge, Tennessee. In this case, since oaks and hickories predominated on the site, the increase in Ca removal due to whole-tree harvesting (after leaf-fall) vs. sawlog harvesting was approximately equal to the increase in biomass removal (about 2.5 times in each case) (Johnson et al. 1982). This was not the case for all species, as the tissue concentration data show for Liriodendron tulipifera L. on the same site (fig. 3). Nor was it the case for N,

Table 3--Nutrient concentrations in 1-year-old stump sprouts and mature bole tissue of three species from the Oak Ridge, Tennessee, whole-tree harvest site (D. W. Johnson and L. K. Mann, unpubl. data on file at Environmental Sciences, Division, Oak Ridge National Laboratory)

Species	N	P	K	Ca
	-----	-----	%-----	-----
Quercus prinus L.				
Stump sprouts*	0.74	0.06	0.48	0.30
Mature stem	0.19	0.01	0.04	0.73
	±0.01	±0.001	±0.016	±0.07
Carya spp.				
Stump sprouts*	0.79	0.08	0.29	0.60
Mature stem	0.17	0.01	0.14	1.01
	±0.01	±0.003	±0.06	±0.15
Liriodendron tulipifera L.				
Stump sprouts[1]	1.16	0.13	0.40	0.47
Mature stem	0.18	0.01	0.03	0.27
	±0.008	±0.008	±0.02	±0.08

[1]Analysis of one bulked sample of chipped stump sprouts, thus no standard deviations of concentrations are available.

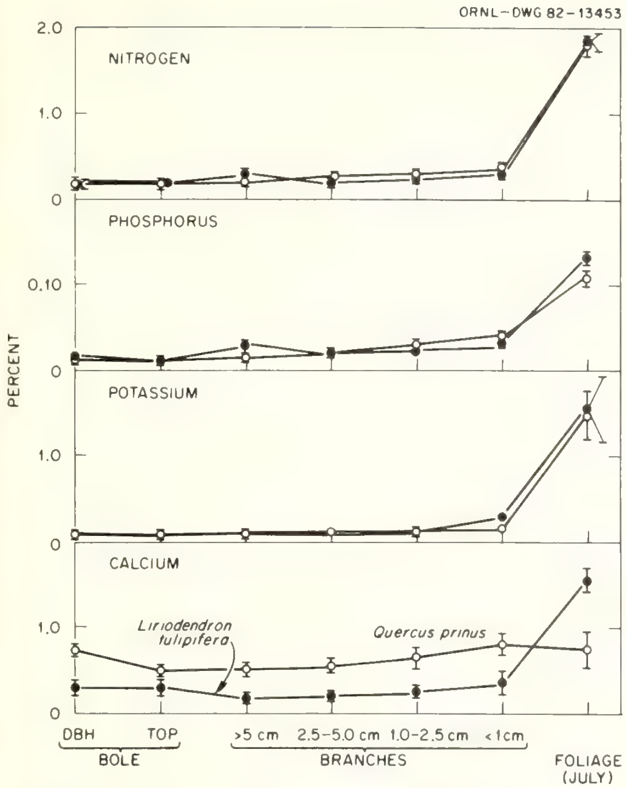

Figure 3.--Nutrient concentrations (percent) in bole (at d.b.h. and top, or just below first major forking), branch (diameter size classes of >5 cm, 2.5-5.0 cm, 1.0-2.5 cm, and <1 cm), and foliage (July 1979) of yellow-poplar (Liriodendron tulipifera L.) and chestnut oak (Quercus prinus L.) from a site near Oak Ridge, Tennessee.

P, or K: Concentrations of those nutrients increased for bole→branch→foliage in all species analyzed. The situation with Ca, however, was the most interesting because nutrient budget data suggested that fertilization will be required to maintain Ca status under intensive harvesting regimes in oak-hickory forests (Johnson et al. 1982).

Since nutrients are usually most concentrated in foliage, conductiong whole-tree harvests in deciduous forests during the dormant season seems logical, thus preventing the low biomass/high nutrient removal associated with foliage. In practice, however, the advantages of this practice are dependent on the amount of nutrients in foliage and the degree to which foliar nutrients are translocated back into other tree tissues prior to abscission. Table 4 lists percent of aboveground nutrients in foliage and percent of aboveground nutrients returned via litterfall and leaf-wash for several deciduous forest sites studied during the International Biological Program. This was summarized and synthesized by Cole and Rapp (1981). There is a great range in the percent of aboveground nutrient content in foliage (from 3 for Ca at Oak Ridge to 58 for K at the Thompson site). In some cases, translocation substantially reduces the return of nutrients to the forest floor by litterfall and leaf-wash (N at Oak Ridge, N and K at the Alaskan site), thus reducing the advantage of harvesting in the dormant season. In other cases, a sizable percent of aboveground nutrient content is returned via litterfall and leaf-wash, and harvesting during the dormant season is distinctly advantageous (i.e., Thompson, Wash; Meathop Woods, United Kingdom).

As these examples show, generalizations about the effects of harvesting various biomass components are questionable. While it is usually true that nutrients are most concentrated in younger tissues, it is not always true, and the exceptions can be important from the perspective of total nutrient removal from sites (especially in the case of Ca). It is also clear that the relative importance of foliage in total nutrient removal is so variable that broad generalizations as to the importance of foliage are hazardous.

EFFECTS OF HARVESTING ON TOTAL NUTRIENT SUPPLY

The amount of nutrients removed by harvesting is affected by biomass, nutrient status species, age, and the degree to which various biomass components are removed. The effect of this removal on site nutrient supplies is a function of total soil nutrient content, atmospheric inputs (including N fixation), and losses due to leaching and erosion over the subsequent rotation. Most studies of conventional rotation, bole-only harvesting concluded that nutrient removals in biomass and by subsequent leaching are not sufficient to warrant great concern (Cole and Gessel 1965, Likens et al. 1978, Wells and Jorgensen 1979). Researchers in various parts of the world concluded, however, that whole-tree harvesting, especially with short rotations, causes significant depletions of one or more nutrients (table 5). The particular nutrient identified varies but is most frequently reported to be Ca. Nitrogen, the nutrient most commonly limiting forest growth under current conditions, is identified only in the Douglas-fir stands of Washington and young hardwood stands of Mississippi and Alabama. In several cases, N is identified as currently limiting growth but is not projected to be a greater problem with intensive harvesting. Reasons for this conclusion vary, but generally relate to the fact that harvesting has a modest effect on total ecosystem N content and that projected atmospheric inputs could offset N removal in harvesting. Ca is identified as a potential limitation by studies in Australia, Canada, Wisconsin, Minnesota, and Tennessee. In all cases, this conclusion is drawn from nutrient budget considerations and in no case does Ca deficiency currently exist. Phosphorus and potassium are identified as potentially limiting with harvesting in young hardwood plantations in Mississippi and Alabama, and phosphorus alone is identified in mixed hardwood-conifer stands in Ontario, again from nutrient budget considerations. No additional nutritional problems are projected with intensive harvesting

Table 4--Percent of aboveground N, P, K, and Ca in foliage and percent returned in litterfall and leaf-wash in several deciduous forest stands (adapted from Cole and Rapp 1981)

			Nitrogen		Phosphorus		Potassium		Calcium	
Location	Age	Species	in foliage	returned	in foliage	returned	in foliage	returned	in foliage	returned
	years		percent							
Oak Ridge, Tennessee	30-150	Chestnut-oak dominated, mixed deciduous	32	18	15	10	29	26	3	6
Hubbard Brook, New Hampshire	60	Northern hardwood	19	16	17	14	19	29	5	11
Meathopwood, United Kingdom	80	Beech-oak	31	26	28	20	18	23	9	22
Kongalund, Sweden	45-130	Beech	11	7	8	6	6	5	4	6
Thompson, Washington	30	Red alder	42	40	22	31	58	69	26	48
Central Alaska	50	Paper birch	23	9	27	27	22	9	9	22

of 20-year-old cottonwood stands in Mississippi (N, P, and K tested) or in jack pine stands in Ontario (except possibly K, with N, P, K, Ca, and Mg tested).

Most undisturbed forest ecosystems show a net loss (output > input) for cation nutrients (Ca, K, Mg) and a net gain for N and P (Abrahamsen 1980, Cole and Rapp 1981). Total budgetary assessment should usually indicate that N and P status is improving while cation nutrient status is declining, despite the fact that far more forests are limited by N and P than by cation nutrients. Total budgetary assessments of harvesting effects often do not account for leaching losses, yet Ca is stil identified as a potential limitation in many cases. Conclusions based on total budgetary information may be quite erroneous, since forests respond to the supply of available nutrients and available nutrients may or may not be a function of total nutrient supply.

EFFECT OF HARVESTING ON SOIL NUTRIENT AVAILABILITY

The effect of harvesting on soil nutrient availability is the least understood yet perhaps the most important aspect of harvesting effects on forest nutrient status and growth. Nitrogen availability is especially difficult to assess and predict (Keeney 1980). Although very few studies of whole-tree harvesting suggest that N will be a limitation, these conclusions must be viewed with caution because they are drawn from considerations of total N budgets, not of potential changes in N availability.

Nitrogen availability is strongly affected by C/N ratio in forest litter and soils (Ellis 1974, Johnson and Edwards 1979, Keeney 1980). The C/N ratio of forest residues left after harvesting may therefore, have a significant impact on soil N availability. In general, the C/N ratio of residues will decrease as the percent of woody biomass removal increases, as illustrated by the examples for a Douglas-fir forest in Washington and a chestnut oak forest in Tennessee (fig. 4). Harvesting 30 of bole biomass results in the removal of 26 and 16 of total aboveground biomass and N, respectively, in the Douglas-fir forest (fig. 4a). Residue left on site has a total C/N ratio of 370 (considering bole, branch, and foliage as one unit) (fig. 4b). A 30 percent bole removal in the chestnut oak forest results in slightly lower percentages of total aboveground biomass (22) and N (14) removal, but residues have a considerably lower C/N ratio due to the higher N concentrations in woody tissues (fig. 4a and b). In both cases, the percent of total aboveground N removal increases with increasing bole removal, but percent aboveground N removal increases less rapidly than percent aboveground biomass removal. This is because of the low N concentration of bole tissue as compared to branch and foliar tissue. (That is, boles constitute a greater proportion of total aboveground biomass than total aboveground N.) The C/N ratio of residues decreases drastically, however, as percent bole removal increases because less bole tissue (with its high C/N ratio) is left on site. Thus, while increasing utilization of woody tissues will cause increases in total N removal from the site, the nitrogen left in non-bole residues is probably more available than that in bole residues. In fact, bole residue, because of its high C/N ratio will probably cause a net reduction in N availability as it decomposes. Thus, site N status and productivity can be temporarily reduced by leaving too much woody residue after harvesting (Bollen 1974). Long-term effects of residues on soil organic matter and N status are probably beneficial, however. The ultimate effects of C/N interactions of forest residues on forest growth will depend on the extent to which the regrowing stand recovers from the short-term N deficiency caused by leaving woody residues (if such a deficiency

Table 5--Brief synopsis of whole-tree harvesting results

Location	Species	Age	Limiting nutrients (others tested)	Comments	Reference
		years			
Karuah, Australia	*Eucalyptus sieberi*, *E. muellarana*	50	Ca (K)	Inputs insufficient	Turner 1981
Thompson, Washington	*Pseudotsuga menziesii* (Bong.) Carr.	42, 73	N (Ca, K, Mg)	Inputs insufficient; currently N-deficient	Cole 1978
Quebec, Canada	*Abies balsamea* (L.) Mill	All-aged	Ca (N,P,K,Mg)	Large removals	Weetman and Webber 1972
	Picea rubens Sarg. *Picea mariana* (Mill.) B.S.P.	65	Ca	Large removals; currently N-deficient, but WTH not thought to cause further N problems	Weetman and Webber, 1972
Mississippi	*Populus deltoides* Bartr.	4	P,K	Using Boyles index	Baker 1978
	Populus deltoides	12	P,K (slight effect)		
	Populus deltoides	20	None		
	Populus deltoides	2	N,P,K		
	Platanus occidentalis L.	2 (N,P,K)	P,K		Baker 1978
New Hampshire	Northern hardwoods	Mixed; partial cut in 1946	None (N,P,K, Ca)	Soil total pools large relative to removal; atmospheric inputs may offset losses	Hornbeck and Kropelin 1982
Wisconsin	Mixed hardwoods	45	None (N,P,K,Ca, Mg)	Good soil, but short rotations may worsen the situation	Boyle and Ek 1972
	Aspen-mixed hardwood	40, but 30-year rotation	Ca (N,P,K)	Nine rotations of Ca available in soil	Boyle et al., 1973
Minnesota	*Pinus resinosa* Ait.	40	Ca (N,P,K,Mg)	More Ca uptake in *Picea glauca* and *Populus tremuloides* than in other stands; Ca limitation thought to be a general problem	Alban et al. 1978
	Pinus banksiana Lamb.	40	Ca		
	Pica glauca (Moench) Voss	40	Ca		
	Populus tremuloides Michx.	40	Ca		
Alabama	*Populus deltoides* Bartr.	6-9	N,P,K (Ca, Mg)	Large soil Ca, Mg pools; leaving foliage on site has little effect	White 1974
Ontario	Mixed wood (ranges from predominantly aspen to white spruce and balsam fir)	?	P (N,K,Ca,Mg)	Very low soil P reserves	Gordon 1981
Tennessee	Mixed upland oak	50-150	Ca (N, P, K)	Low soil pools, inputs insufficient	Johnson et al. 1982
Ontario	*Pinus banksiana* Lamb.	65	None identified, possibly K (N,P,Ca,Mg)	Inputs seem to offset losses	Morrison and Foster 1979

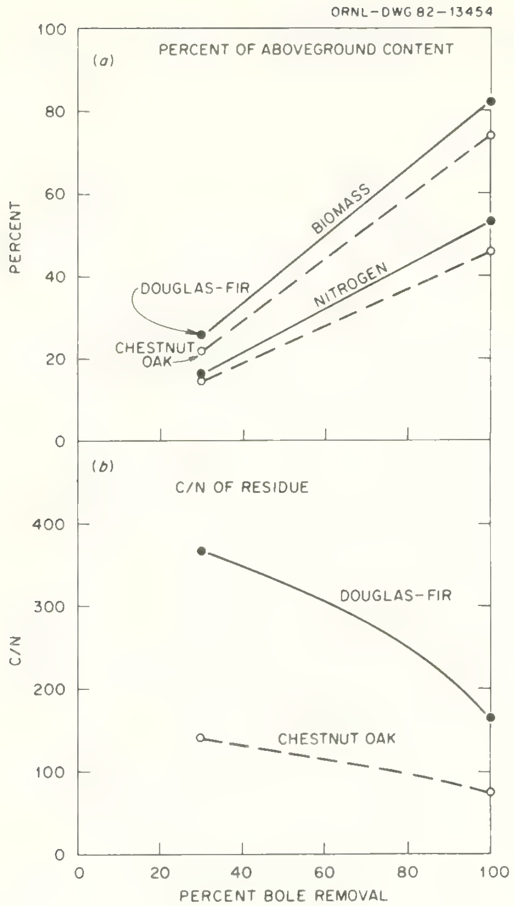

Figure 4.--(a) Changes in removal of percent of total aboveground (i.e., bole + branch + foliage) biomass and N removal with increasing bole removal in a 42-year-old Douglas-fir forest in Washington and a 30- to 80-year-old chestnut oak forest in Tennessee. (b) Changes in C/N ratio of residues with increasing bole removal in the forests (described in 4a) (data adapted from Cole and Rapp 1981).

occurs). After this stage, the regrowing stand may respond to the long-term improvements in soil organic matter and N status caused by leaving residues. This in turn depends on decomposition rate, which in turn is affected by temperature, moisture, aeration, pH, nutrient supply, and a variety of complex biological interrelationships. One might expect the period of N deficiency to be shorter in warm temperate or tropical ecosystems with inherently high decomposition rates. Only long-term studies of forest growth and N cycling can provide true answers to these questions, however, and such answers are bound to be highly site specific.

The availability of nutrient cations and P to the regrowing forest will be strongly affected by soil weathering rates (Clayton 1979). Unfortunately, weathering rates are usually unknown or only poorly known. Furthermore, weathering rates can be affected by trees themselves. Boyle and Voigt (1973) found that organic acids exuded from pine roots (and associated fungi) were effective in weathering silicate minerals. The numerous forecasts of potential Ca deficiency due to intensive harvesting must therefore be regarded as tentative.

SUMMARY AND CONCLUSIONS

It is relatively easy to obtain information on biomass and nutrient distribution in various stands, and a considerable amount of such information is available. From these data, it is clear that nutrient removal in harvesting can be strongly influenced by species, age, nutrient status, and the degree to which various biomass components are harvested. Broad generalizations about such effects are not reliable, however, because important exceptions to the general rule do occur. It cannot be safely stated that deciduous species contain more nutrient per unit biomass than do coniferous species, but generalizations at the genus or species level may have some validity. Biomass and nutrient accumulations during stand development are documented for some even-aged, single-species, coniferous forests, perhaps allowing some generalizations about rotation age effects, but very little is known about stand age effects in uneven-aged or mixed-species forests. In many cases, nutrients (especially N, P, and K) are most concentrated in younger tissues (foliage, small branches), and thus whole-tree harvesting causes greater increases in nutrient removal than in biomass yield. There are exceptions, however, especially with respect to Ca accumulations in mature woody tissues of some species.

Combining the information on nutrient removal in harvesting with information on soil nutrient pools, atmospheric inputs, and losses from leaching provides an overall picture of the importance of harvesting to site nutrient status. In many significant ways, however, this picture is incomplete. Changes in soil nutrient availability time are nearly impossible to predict at present. Because trees respond to available rather than total nutrient supplies, this lack of knowledge precludes meaningful predictions of the effects of harvesting in soil nutrient status and forest productivity in all but the most extreme situations (e.g., where total soil supplies are very low) and constitutes a real research need.

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EFFECTS OF HARVESTING INTENSITY ON NUTRIENT LOSSES AND FUTURE PRODUCTIVITY IN HIGH AND LOW PRODUCTIVITY RED ALDER AND DOUGLAS-FIR STANDS

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ABSTRACT: High- and low-productivity stands of red alder and Douglas-fir were subjected to three intensities of harvest: bole only, whole tree, and complete aboveground biomass removal. Increased harvest intensity was found to increase nutrient losses disproportionately compared with the increase in biomass obtained. Harvesting of alder dramatically reduced the leaching of nitrate. Cation leaching was also reduced on alder sites following harvesting. Growth of Douglas-fir seedlings reflected forest site conditions and harvest intensity.

INTRODUCTION

Recent emphasis on complete utilization of forest components as biomass for fiber and energy may cause a dramatic increase in future harvesting intensity. Increased utilization through whole-tree harvesting or residue removal has important implications for forest productivity. Whole-tree harvesting in which all aboveground biomass is removed can yield as much as 300 percent more biomass when compared with traditional timber harvesting (Keays and Hatton 1975). This increase in harvest intensity selectively removes organic matter of higher nutrient content than that of merchantable logs. Malkonen (1976) obtained a 2- to 5-fold increase in nutrients removed during whole-tree harvesting. These added nutrient losses could be significant particularly in areas of low fertility. In addition post harvesting leaching losses could be altered by intensified biomass removal.

To evaluate the impact of increased utilization on nutrient losses and future forest productivity, we have initiated a study on two prominent Pacific Northwest tree species. This study is a part of a larger research effort coordinated through Oak Ridge National Laboratory. Study sites for this program were chosen to include the northwestern deciduous-coniferous forest (reported here) as well as central and northern hardwoods, northern coniferous forests, southern appalachian oak hickory forests, and southern pine forests (reported by other investigators). These sites were located in a variety of geographic regions to allow a wide comparison between forest types.

This study had several objectives. The first was to determine, at the ecosystem level, the nutrient and organic matter losses due to various levels of harvesting in high- and low-

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productivity Douglas-fir and red alder stands. The second was to ascertain to what extent leaching of nutrients from the soil contributed to nutrient depletion of the site. The third was to establish what effects nutrient and organic matter removal had on growth and mortality of seedlings at the sites examined.

METHODS

This research was conducted at the Charles L. Pack Forest, the teaching and research forest of the College of Forest Resources, University of Washington. Pack Forest is located approximately 100 km south of Seattle against the foothills of the Cascade Range.

High- and low-productivity stands of 53-year-old red alder (Alnus rubra Bong.) and Douglas-fir (Pseudotsuga menziesii (Mirbel) Franco) were examined. All four sites were located within a 2-km^2 area. Each stand was subjected to four levels of harvesting: control (no harvest), bole-only, whole-tree, and complete aboveground biomass removal.

To minimize nutrient loss, alder and Douglas Fir stands were clearcut during the winter of 1980 following foliage drop. Duplicate 20-m^2 plots were established for each site-productivity treatment. The high-productivity site is flat terrain of glacial origin deposited during the Vashon glaciation, approximately 10,000 years ago. The residual soil (low productivity) is an andesite material on a moderate slope.

The harvested Douglas-fir sites were immediately reestablished with 2-year-old Douglas-fir seedlings approximately 54 cm tall. Alder was allowed to regenerate naturally on the alder sites. Yearly growth measurements have been completed for the Douglas-fir but not for the alder as an additional year was needed to attain full site occupancy.

Prior to harvesting, 100 percent of the trees on the sites were examined and species, crown class, and diameter at breast height were recorded. The understory vegetation was sampled for all sites using four 1-m^2 subplots per plot. Material was dried, weighed, digested using a lithium sulfate sulfuric acid procedure (Parkinson and Allen 1975), and analyzed for total nitrogen and phosphorus. Potassium was determined using the atomic absorption photospectrometer. Forest floor collections were made using four 30-cm^2 subplots per plot. Samples were treated as above and assayed for nitrogen, phosphorus, and potassium. Soil samples were collected from six sample points per plot. Sampling depths included the 0-10-cm and 11-50-cm zones. Bulk density was determined for each sample. Samples were then combined by plot and analyzed for total Kjeldahl nitrogen using the lithium-sulfate sulfuric acid digest. Total carbon was assayed using a Leco induction furnace.

Tension lysimeters were installed in triplicate during fall 1980 (for a complete description of tension lysimeters, see Cole 1968). Six-inch diameter lysimeter plates were installed at the 10-cm soil depth; tube lysimeters were installed at 50 cm. The use of continuous tension lysimeters allowed for an uninterrupted sampling of the soil solution during periods of soil moisture flow. Samples were collected every 4 weeks when sufficient flow was available and analyzed in the chemical laboratory of the College of Forest Resources, University of Washington. Total nitrogen and phosphorus were assayed by a sulfuric acid-peroxide digest and determined on the Auto Analyzer. Calcium, Mg, Na, and K levels were determined using straight filtered samples on the atomic absorption spectrophotometer and PO_4, NO_3, NH_4, SO_4, and Cl, using the auto analyzer. Total alkalinity, pH and total conductivity were determined using established methods. Leaching losses were calculated on the basis of monthly precipitation, and corrected for transpiration losses.

RESULTS AND DISCUSSION

Biomass and Nutrients Present Prior to Harvesting

The organic matter and nitrogen distributions within the high- and low-productivity alder and Douglas-fir sites are presented in table 1. The alder high site has a greater accumulation of organic matter (318 000 kg/ha) than the low alder site (302 000 kg/ha), due mainly to a greater amount of aboveground biomass. Belowground biomass and nitrogen levels are similar for both alder sites.

Major differences in the organic matter accumulation on the Douglas-fir sites occur in all components. The high site has more biomass in the bole (281 000 kg/ha) and in the soil (139 000 kg/ha) than does the low site (134 000 kg/ha and 52 100 kg/ha, respectively). The low site has a greater amount of biomass in the understory (2 240 kg/ha) than does the high site (592 kg/ha). This reflects the more open aspect of the low-site canopy which permits higher irradiance levels lower in the canopy. High-site biomass exceeds that of low-site biomass in all other components.

The high-productivity Douglas-fir site has greater nitrogen than the low site in all components except the understory. The low site bole has 66 percent less nitrogen than does the high site but only 42 percent less biomass. Soil nitrogen was nearly five times higher in the 0-10-cm zone and three times as high in the 11-50-cm zone. This indicates that the Douglas-fir high site is either not nitrogen limited or is relatively less so than the low site.

Soil carbon and nitrogen values comprise the major differences between alder and Douglas-fir sites. The alder sites have approximately twice the nitrogen found at the Douglas-fir high site and nine times that found at the low site for the 0-10-cm zone and six times as much in the low site 11-50-cm zone.

The distribution of phosphorus and potassium on these four sites is summarized in table 2.

Table 1--Distribution of biomass and nitrogen in high- and low-productivity red alder and Douglas-fir stands (kg/ha)

		Alder				Douglas-fir			
		High		Low		High		Low	
		Biomass	N	Biomass	N	Mass	N	Mass	N
Foliage	$\bar{X}$	9930	263	6060	145	12300	148	11100	113
	SD	1140		982		2470		2530	
Branches	$\bar{X}$	9980	60	9270	67	24800	102	19700	51
	SD	1750		2090		3980		3220	
Bole	$\bar{X}$	137000	287	111000	311	281000	478	134000	161
	SD	17800		16800		58100		27500	
Tree Total		157000	610	126000	523	318000	728	165000	325
Understory	$\bar{X}$	1720	29.1	1900	32.2	592	6.5	2240	14.0
	SD	790		1040		430		935	
Above ground Total		159000	639	128000	555	319000	735	167000	339
Forest Floor	$\bar{X}$	15000	327	14100	330	17600	214	13900	187
	SD	2740		1151		1300		1390	
Soil 0-10 cm	$\bar{X}$	35400	1280	34100	1160	25800	578	8670	125
	SD	8200		7610		8400		4650	
Soil 11-50 cm	$\bar{X}$	108100	2320	126000	2540	95800	1480	29500	358
	SD	47600		19000		33100		16800	
Soil & Forest Floor Total		159000	3930	174000	4030	139000	2280	52100	670
System Total		318000	4560	302000	4590	458000	3011	219000	1000

Table 2--Distribution of phosphorus and potassium in high- and low-productivity red alder and Douglas-fir stands (kg/ha)

		Alder				Douglas-fir			
		High		Low		High		Low	
		P	K	P	K	P	K	P	K
Foliage	$\bar{X}$	20.7	173.0	9.3	64.0	27.1	64.0	22.1	48.0
Branches	$\bar{X}$	6.0	23.0	4.7	21.3	12.4	37.3	6.8	12.1
Bole	$\bar{X}$	41.0	151.0	22.2	122.0	56.3	225.0	26.9	81.0
Tree Total		68	346	36.2	208	96	326	56	140
Understory	$\bar{X}$	2.4	23.2	2.4	23.4	0.8	5.5	3.0	12.7
Above ground Total		70	370	39	231	97	332	59	153
Forest Floor	$\bar{X}$	20.3	30.3	16.5	21.7	20.9	25.9	18.8	27.1
Total		91	400	55	253	118	358	78	180

Aboveground phosphorus and potassium are 1.8 and 1.6 times as high in the high-productivity alder site as in the low. The high alder site has more biomass in these components but not sufficient to explain the differences. This may indicate luxury consumption of these nutrients on the high site with storage occurring preferentially in the bole and foliage. Values for phosphorus in the understory and litter of the alder sites are similar.

The high-site Douglas-fir has 1.5 and 2.0 times more phosphorus and potassium, respectively, than has the low site. The high site has more of these nutrients in all but one component with the bole making the largest contribution. The low site has higher values of both nutrients in the understory because of greater understory biomass.

Nutrient and Biomass Losses from Harvesting

Nutrient losses increased substantially with increased harvesting intensity. The largest losses occurred on the high-productivity sites (table 3). Harvesting the bole only on the alder high-productivity site removed 43 percent of the site biomass but only 6 percent of the nitrogen. Increasing harvesting to complete removal of aboveground biomass yielded an additional 11 percent biomass, but more than tripled nitrogen losses and almost doubled phosphorus and potassium losses. Low-productivity alder losses are comparable. The complete biomass removal netted 10 percent more biomass than the bole-only treatment but almost tripled the nitrogen losses.

Bole-only harvesting on the Douglas-fir high-productivity site removed 61 percent of the total aboveground biomass and 16 percent of the nitrogen. Increasing harvesting to include all aboveground biomass doubled nitrogen removal but yielded only another 12 percent biomass. Nutrient losses on the Douglas-fir sites were significantly higher than on the alder sites.

The smallest nutrient loss resulting from harvesting was on the Douglas-fir low-productivity site. This site, however, had the greatest percentage loss due to overall low nutrient capital present. This was particularly true for the complete removal harvest. There is a relatively wide ratio between organic matter content and nutrients in the bole and a narrower ratio for the other ecosystem components. Thus, the whole-tree harvest and complete biomass removal will cause a greater nutrient drain per unit organic matter removed. Harvesting losses will have a greater impact on this site than the other sites examined.

These results indicate that on all sites, increased levels of harvesting yielded disproportionately larger losses of nutrients from the ecosystems. These additional losses could be particularly critical in the case of the low productivity Douglas-fir site.

Control Soil Solution Concentrations

Soil solution concentrations at the high alder site were very different from the other sites examined. The alder site had significantly greater concentrations of anions and cations in the soil solutions at both the 10- and 50-cm depths (table 4). The average monthly concentration of anions in the soil solution at 50 cm was 8.2 ± 2.7 meq/l in the high alder site as compared with approximately 1.25 to 2.25 meq/l for the other sites. Higher levels of HCO_3, NO_3, Mg, Ca, and K were found in samples obtained from this site. Concentrations of HCO_3 at 50 cm averaged 6.7 ± 2.0 meq/l in the high alder site but were less than 2.0 meq/l at the other sites (table 5). The dominant anion in the alder high site soil solution was NO_3 (70 percent of anion losses) at the 10-cm depth. At 50 cm this changed to an HCO_3 (80 percent of anion loss) dominated system. The major cation in the solution at 10 cm was Mg which comprised 63 percent of all cation losses at this site. This had shifted to only 30 percent at the 50-cm depth with Ca replacing it as the major cation in solution (57 percent).

The low-alder site had less NO_3 in absolute terms in the soil solution than did the high site (1.2 ± 0.5 meq/l and 0.47 ± 0.5 meq/l, respectively). This is surprising as total soil nitrogen values for these sites were very similar. The low alder anion concentration was less dominated by NO_3 (30 percent of anion losses) at 10 cm while HCO_3 made up a significant portion of the anions at that depth. At 50 cm the low alder soil solution was also dominated by the HCO_3 anion.

The high and low Douglas-fir sites had lower absolute solution concentrations than the high alder site. Sulfate and Cl made up 30 percent to 40 percent each of the anions at 10 cm with HCO_3 becoming more important at 50 cm (table 6). At the high Douglas-fir site, HCO_3 comprised 90 percent of the anions present in the soil solution at 50 cm. Sodium and K were relatively more important components of the Douglas-fir site soil solution than they were at the alder sites. There was no significant amount of NO_3 in the soil solution at either Douglas-fir site.

Changes in Soil Solution with Harvesting

The effects of harvesting on the concentrations of ions in the soil solution at the alder high site were dramatic. Increasing the amount of material removed by harvest had little additional effect on the concentration of ions in the soil solution. Expressed as average monthly concentrations, there was a large reduction in total cations and anions in the soil solution at both depths (table 5). Harvesting reduced anions at 50 cm from 8.22 ± 2.7 meq/l to less than 2.5 meq/l.

The most dramatic reduction following harvesting of alder has been a reduction in the nitrate concentration at both 10 and 50 cm. As previously indicated, nitrate concentrations in the soil solution under the alder high site were quite substantial. Cutting the alder reduced the average monthly 50-cm concentration of nitrate from 1.17 ± 0.5 meq/l in the control to 0.11 ± 0.11 meq/l in the whole tree removal treatment--

Table 3--Biomass and nitrogen removal due to harvesting (kg/ha) (includes soils values 0-50 cm)

	Biomass		Nitrogen	
	Remaining	% Removed	Remaining	% Removed
Alder high				
Bole only	181000	43	4280	6
Whole tree[1/]	171000	46	3930	8
Complete	143100	54	3600	21
Alder low				
Bole only	191000	37	4270	7
Whole tree[1/]	182000	40	4060	9
Complete	160000	47	3700	19
Douglas-fir high				
Bole only	177000	61	2530	16
Whole tree	140700	70	2280	24
Complete	122400	73	2060	32
Douglas-fir low				
Bole only	85000	61	848	16
Whole tree	54900	75	684	32
Complete	38000	82	483	52

[1/] Does not include foliage due to winter harvesting.

Table 4--Average monthly anion concentrations (meq/l) of soil solutions collected at 10 and 50 cm depths for four sites and four harvest treatments during 1981 (n = 5-8)

		Control	Bole only	Whole tree	Complete removal
		10-cm depth			
Alder high	$\bar{X}$	1.20	0.34	0.34	0.16
	SD	±0.17	±0.04	±0.11	±0.03
Alder low	$\bar{X}$	0.54	0.39	0.35	0.48
	SD	±0.17	±0.10	±0.06	±0.18
Douglas-fir high	$\bar{X}$	0.45	0.57	0.46	0.26
	SD	±0.07	±0.13	±0.21	±0.09
Douglas-fir low	$\bar{X}$	0.90	0.39	0.40	0.44
	SD	±0.32	±0.10	±0.14	±0.06
		50-cm depth			
Alder high	$\bar{X}$	8.22	2.54	2.07	2.39
	SD	±2.71	±0.49	±0.54	±0.50
Alder low	$\bar{X}$	1.69	1.64	1.30	1.30
	SD	±0.54	±0.38	±0.16	±0.25
Douglas-fir high	$\bar{X}$	2.17	1.89	2.18	1.89
	SD	±0.93	±0.45	±1.02	±0.49
Douglas-fir low	$\bar{X}$	1.32	0.89	0.95	1.03
	SD	±0.16	±0.09	±0.05	±0.84

Table 5--Average monthly concentrations of ions (meq/l) leached from high- and low-productivity alder sites at the 50 cm soil depth for four harvesting treatments during 1981 (n = 5-8)

		C[1]	BO[2]	WT[3]	CP[4]		C	BO	WT	CP
High-productivity alder										
HCO_3	$\bar{X}$	6.678	2.374	1.791	2.343	NH_4	0.005	0.001	0.001	0.002
	SD	± 2.026	±1.69	±0.652	±0.470		±0.005	±0.001	±0.001	±0.003
NO_3	$\bar{X}$	1.168	0.053	0.114	0.006	Na	0.249	0.172	0.173	0.102
	SD	± 0.503	±0.053	±0.112	±0.012		±0.154	±0.103	±0.103	±0.05
PO_4	$\bar{X}$	0.001	0	0	0	K	0.189	0.061	0.056	0.013
	SD	±0.003	0	0	0		±0.067	±0.007	±0.012	±0.007
SO_4	$\bar{X}$	0.380	0.094	0.123	0.054	Ca	2.265	1.627	1.505	1.591
	SD	±0.252	±0.015	±0.036	±0.018		±0.987	±0.463	±0.377	±0.635
Cl	$\bar{X}$	0.066	0.034	0.037	0.015	Mg	4.547	0.849	0.557	0.536
	SD	±0.063	±0.017	±0.029	±0.008		±3.459	±0.227	±0.225	±0.153
Low-productivity alder										
HCO_3	$\bar{X}$	1.030	1.380	1.142	1.077	NH_4	0.006	0.005	0	0.003
	SD	±0.230	±0.315	±0.116	±0.182		±0.008	±0.007	±0.005	±0.004
NO_3	$\bar{X}$	0.473	0.075	0.003	0.030	Na	0.187	0.023	0.225	0.262
	SD	±0.541	±0.102	±0.003	±0.040		±0.129	±0.033	±0.029	±0.023
PO_4	$\bar{X}$	0	0	0	0	K	0.030	0.022	0.019	0.039
	SD	0	0	0	0		±0.008	±0.008	±0.004	±0.060
SO_4	$\bar{X}$	0.130	0.178	0.131	0.168	Ca	0.880	1.018	0.705	0.685
	SD	±0.089	±0.044	±0.044	±0.055		±0.249	±0.208	±0.136	±0.149
Cl	$\bar{X}$	0.041	0.048	0.042	0.054	Mg	0.316	0.374	0.298	0.282
	SD	±0.051	±0.032	±0.037	±0.050		±0.185	±0.120	±0.044	±0.064

[1] C = Control
[2] BO = Bole only
[3] WT = Whole tree
[4] CP = Complete removal

Table 6--Average monthly concentrations of ions (meq/l) leached from high and low productivity Douglas-fir sites at the 50 cm soil depth for four harvesting treatments during 1981 (n = 5-8)

		C[1]	BO[2]	WT[3]	CP[4]		C	BO	WT	CP
High-productivity Douglas-fir										
HCO_3	$\bar{X}$	1.94	1.63	2.03	1.61	NH_4	0.001	0.001	0.004	0.002
	SD	0.942	0.313	1.01	0.473		0.001	0.001	0.005	0.002
NO_3	$\bar{X}$	0	0.001	0	0	Na	0.166	0.253	0.168	0.174
	SD	0	0.002	0	0		0.082	0.023	0.127	0.031
PO_4	$\bar{X}$	0	0	0.004	0.003	K	0.059	0.066	0.079	0.127
	SD	0.001	0	0.002	0.004		0.006	0.013	0.015	0.017
SO_4	$\bar{X}$	0.164	0.133	0.123	0.095	Ca	0.934	1.164	1.729	1.011
	SD	0.028	0.036	0.062	0.123		0.190	0.263	0.622	0.432
Cl	$\bar{X}$	0.070	0.049	0.042	0.105	Mg	0.465	0.391	0.642	0.493
	SD	0.016	0.029	0.032	0.033		0.133	0.072	0.146	0.183
Low-productivity Douglas-fir										
HCO_3	$\bar{X}$	0.729	0.620	0.689	0.513	NH_4	0.002	0.004	0.002	0.004
	SD	0.180	0.140	0.108	0.098		0.002	0.005	0.001	0.004
NO_3	$\bar{X}$	0	0.013	0.066	0.076	Na	0.221	0.234	0.163	0.325
	SD	0	0.028	0.064	0.076		0.056	0.086	0.068	0.106
PO_4	$\bar{X}$	0.001	0	0	0	K	0.104	0.033	0.071	0.121
	SD	0.001	0	0	0		0.020	0.012	0.021	0.022
SO_4	$\bar{X}$	0.481	0.155	0.144	0.215	Ca	0.764	0.444	0.657	0.537
	SD	0.168	0.063	0.033	0.108		0.299	0.090	0.060	0.083
Cl	$\bar{X}$	0.167	0.057	0.059	0.155	Mg	0.501	0.181	0.245	0.283
	SD	0.062	0.025	0.023	0.030		0.150	0.032	0.099	0.022

[1] C = Control
[2] BO = Bole only
[3] WT = Whole tree
[4] CP = Complete removal

a 10-fold reduction. Nitrate concentrations were reduced even further under other treatments. The relative amount of NO_3 also changed. Nitrate comprised 14 percent of all anions in the control plot while HCO_3 comprised 81 percent. After harvesting, the percentage of NO_3 leached relative to total anion losses ranged from 6 percent for the whole tree to 0.3 percent for the complete treatment. Due to the reduction in the other anions, particularly nitrate, the relative amount of HCO_3 was increased to as high as 98 percent in the complete treatment.

To confirm that this reduction in nitrate was a true representation of soil solution conditions, the duplicate control and complete removal plots were sampled at 10 and 40 cm and extracted in the laboratory with KCl. This data (table 7) fully confirms the lysimeter results and clearly indicates a marked reduction in the soil nitrate concentrations following harvesting. At 50 cm, the alder high-site control had 2.63 ± 1.11 ppm NO_3, while the complete removal treatment had only 0.076 ± 0.027 ppm.

Table 7--Concentration of soil NO_3 and NH_4 nitrogen extracted with KCl at two depths from the high productivity alder sites.

		NO_3-N	NH_4-N	Total N
		ppm		
Control 10 cm	$\bar{X}$	4.95	1.69	6.64
	SD	± 1.33	±0.75	± 1.12
Control 40 cm	$\bar{X}$	2.63	1.27	3.90
	SD	± 1.11	±0.10	± 1.07
Complete removal 10 cm	$\bar{X}$	0.104	2.09	2.19
	SD	± 0.009	±0.13	± 0.14
Complete removal 40 cm	$\bar{X}$	0.076	1.50	1.58
	SD	± 0.027	±0.04	± 0.05

The concentration of NO_3 leached from the harvested plots appears to be further decreasing with time during the second year since harvesting. This may reflect the slow disappearance of excess NH_4 from the system following removal of the alder trees. More data is needed to substantiate this observation. As the site has been reestablished with seedlings, it would be expected that the NO_3 concentrations would increase to the original levels with time.

The concentration of HCO_3 at the high alder site was also reduced by logging. Control values 6.68 ± 2.03 meq/l were reduced to less than 3 meq/l. There was also a significant reduction in cation concentrations in the 50-cm soil solution. The calcium concentration was reduced 30 percent, and Mg was reduced from 4.55 ± 3.5 meq/l to approximately 0.65 meq/l. Magnesium comprised 63 percent of the cation losses prior to harvest but only 30 percent afterwards. The alder high productivity site has changed from a system dominated by Mg cation leaching to one which, after harvesting, is dominated by Ca. Thus, not only has the absolute level of ions in solution been reduced, but the relative proportions of the ions making up the solution have changed as well.

The effects of harvesting on the soil solution of the low-productivity alder site was less dramatic. Here also, increasing the amount of material removed did not increase the impact on the soil solution concentrations. There was little if any reduction in the concentrations of total anions or cations with harvesting at the low alder site. Harvesting did reduce the concentration of NO_3 but not as much as at the high site. Nitrate concentrations were reduced from 0.18 ± 0.11 meq/l to less than 0.050 meq/l at 10 cm and from .47 ± 0.54 meq/l to 0.07 meq/l or less at 50 cm. Here also leaching of NO_3 appears to decrease with time after harvest. The relative proportions of the cations in solution do not change markedly following harvesting. The only change in the composition of the anions is the disappearance of NO_3.

The solution concentrations at the Douglas-fir high and low sites were far less affected by timber harvesting than the alder sites. Again the intensity of the biomass harvest did not have significant impact on the solution concentrations at these sites. Concentrations of ions at the Douglas-fir high-productivity site were not affected by harvesting. The total anion concentration at the low site was reduced from 0.90 ± 0.37 meq/l to approximately 0.40 meq/l at 10 cm. This affect was absent at 50 cm (table 4).

There was no NO_3 in the soil solution at the Douglas-fir sites prior to harvesting. With harvesting, however, some nitrate (0.08 meq/l) was observed at the Douglas-fir low site. No significant changes in the concentrations of individual ions were observed in the Douglas-fir high site. The low site had reduced concentrations of Cl, SO_4, Mg, Ca, and K. The most pronounced change was in the Cl concentration at 10 cm, which was reduced from 0.22 ± 0.04 meq/l to approximately 0.08 meq/l. A similar reduction was observed at 50 cm.

Second Year Control Solution Concentrations

Trends in the soil solution concentrations of the four sites established during the first year were still evident during the second year despite what appears to be a large annual variation in leaching. The most significant change was an overall reduction in ion concentration for all sites and treatments including controls. Higher solution concentrations during the first year may have been a result of disturbance to the system during harvesting, sampling, or lysimeter installation.

Reduction in the solution concentration of various elements was still pronounced, specifically HCO_3 and NO_3 in the alder sites. The major cation in solution at the alder high site was changed from Mg to Ca. Calcium comprised 60 percent of the cations in the soil solution during the second year. This change brought the alder high site in line with the other sites, all of which experienced greater Ca than Mg leaching.

Leaching Losses

Average monthly rates of nutrient removal from the control sites (tables 8 and 9) indicate inherent differences between these ecosystems. Nitrogen leaching, primarily in the form of nitrate, was far higher under the alder stands than the Douglas-fir stands. Leaching of this ion past the 50-cm soil depth was 2.69 ± 4.08 kg/ha at the low alder site and 14.2 ± 16.3 kg/ha at the high alder site. Principal cation leaching components at the high alder site were Mg (58.7 ± 76.3 kg/ha) and Ca (31.4 ± 27.8). Nitrate leaching losses from the Douglas-fir sites were negligible (0.001 ± 0.002 kg/ha).

The largest changes in leaching due to harvesting and residue removal occurred for the alder stands. Contrary to that found at the Douglas-fir sites and other literature on the subject (Cole and Gessel 1965, Likens et al. 1970, Brown et al. 1973), harvesting the alder sites substantially reduced nitrate removal due to leaching. Fifty-cm losses at the alder high site were reduced from 14.2 ± 16.3 to less than 2 kg/ha during the first year following removal. The greatest reduction in leaching was found at the complete harvest site where post harvesting leaching of NO_3 was 0.118 ± 0.243 kg/ha.

The reason for this decrease in nitrate leaching is not known at this time. It could be postulated, however, that the removal of the alder stopped nitrogen fixation. The excess carbon at these sites resulted in the immobilization of the remaining available soil nitrogen. The process of nitrification would thus stop or drastically slow down and thereby decrease the subsequent nitrate levels in the soil solution.

This marked decrease in nitrate leaching following harvesting on the alder sites has the potential of decreasing cation losses from these sites. This would happen only if the concentration of the other anions in the soil solution remained unchanged or also decreased. This, in fact, appeared to be the case. Leaching rates of all cations were reduced subsequent to harvesting in the high-productivity alder stand. Calcium was reduced from 31.4 ± 27.8 kg/ha to less than 15 kg/ha. Magnesium leaching was reduced from 58.7 ± 76.3 kg/ha to less than 5 kg/ha.

Harvesting Douglas-fir sites resulted in a slight and highly variable increase in nitrate leaching. This increase was most evident at the low site. This loss was less than 1 kg/ha. There was no significant effect of harvesting intensity on NO_3 leaching rates. Harvesting did not markedly increase or decrease leaching rates of any other soil solution constituent. Site-to-site variability could have masked any changes at the Douglas-fir sites that might have been triggered by harvesting and residue removal.

Comparison of Harvest and Leaching Losses

Harvesting and leaching losses are directly compared in table 10. The leaching data reflects potential losses at 50 cm over a 1-year period. It should be noted that nutrients leaching past 50 cm do not necessarily constitute a loss to the system. Consequently, figures for leaching losses in table 10 represent maximum values.

The high- and low-productivity alder sites experienced reduced levels of leaching following logging. This resulted in a net savings of nutrients to these ecosystems. This effect was particularly pronounced in the high alder site where bole-only harvesting resulted in a net annual savings of 136 kg/ha nitrogen. This occurred for both nitrogen and potassium at both alder sites. This reduction in leaching could be viewed as conserving nutrients, making up in part for losses suffered during harvesting.

Harvesting Douglas-fir sites did not result in reduced leaching levels with the exception of K leaching at the low-productivity site. Nutrient losses at these sites were small when compared with harvesting losses. The largest loss was for K (11.1 kg/ha/yr) at the Douglas-fir high site. This loss constituted approximately 3 percent of losses associated with logging. Typically leaching contributed less than 1 percent to the total site losses.

Growth of Seedlings Following Harvesting

Two years of Douglas-fir height growth are summarized in table 11. Typically, it is premature to expect significant growth differences between treatments after only two growing seasons as several years are required for seedlings to become established and fully reflect the nutrient and moisture conditions of the site. In this case, site-dependent differences in seedling growth are already evident. There is a clear difference in height growth between the high and low Douglas-fir sites (table 11). On the high-productivity site, height growth averages over twice that noted for the low site (26-cm and 12-cm respectively).

Seedling mortality is substantially greater at the low productivity site (27 percent) than at the high site (8 percent) (table 12). This value is significant at the 99 percent confidence level. The three treatment levels, however, had no statistically significant impact on survival.

A systematic reduction in growth directly parallel to harvest intensity is apparent at the Douglas-fir low site. The average height growth increment after 2 years for the bole-only plots was 15 cm, for whole-tree plots 12 cm, and for the complete-removal plots 9 cm. Similarly, the complete-removal plots at the high-site area also had the slowest growth rates as compared to the whole-tree and bole-only plots. The growth difference between bole-only and whole-tree plots was not significant. Several more growing seasons will be required to determine the long-term significance of these early trends.

Table 8--Average monthly leaching (kg/ha) during 1981 from the 50 cm soil depth for alder high and low productivity based on monthly precipitation.[1/]

		C[2/]	BO[3/]	WT[4/]	CP[5/]		C	BO	WT	CP
High productivity										
$\bar{X}$	NO_3	14.2	0.518	1.70	0.118	NH_4	0.073	0.008	0.007	0.010
SD		16.3	0.687	2.03	0.243		0.122	0.007	0.006	0.013
$\bar{X}$	PO_4	0.004	0.001	0.001	0.001	Na	5.49	1.89	1.74	1.17
SD		0.003	0.000	0.000	0.001		6.62	1.33	1.17	0.815
$\bar{X}$	SO_4	6.30	0.884	1.27	0.520	K	5.28	1.19	1.25	0.338
SD		8.44	0.926	1.57	0.653		5.85	0.991	1.21	0.331
$\bar{X}$	Cl	2.94	0.655	0.568	0.232	Ca	31.4	14.9	14.1	15.0
SD		4.22	0.605	0.409	0.170		27.8	12.2	12.7	12.3
						Mg	58.7	4.90	3.91	3.52
							76.3	3.75	4.74	3.04
Low productivity										
$\bar{X}$	NO_3	2.69	0.886	0.012	0.509	NH_4	0.045	0.036	0.025	0.014
SD		4.08	1.60	0.020	0.981		0.081	0.030	0.039	0.007
$\bar{X}$	PO_4	0.001	0.001	0.001	0.001	Na	1.51	2.96	3.13	3.91
SD		0.001	0.001	0.000	0.001		1.99	2.52	2.42	3.07
$\bar{X}$	SO_4	1.94	1.91	1.40	2.13	K	0.679	0.559	0.879	0.663
SD		3.11	1.81	1.16	1.99		0.902	0.590	0.922	0.338
$\bar{X}$	Cl	0.515	0.962	0.802	1.10	Ca	9.09	11.0	8.91	8.69
SD		0.417	0.867	0.526	0.861		11.1	8.64	7.46	6.46
						Mg	2.55	2.40	2.26	2.20
							3.53	1.94	1.86	1.73

[1/] Includes only months during which precipitation occurred (n=8).
[2/] C = Control
[3/] BO = Bole only
[4/] WT = Whole tree
[5/] CP = Complete removal

Table 9--Average monthly leaching (kg/ha) during 1981 from the 50 cm soil depth for Douglas-fir high and low productivity based on monthly precipitation.[1/]

		C[2/]	BO[3/]	WT[4/]	CP[5/]		C	BO	WT	CP
High productivity										
$\bar{X}$	NO_3	0.001	0.024	0.001	0.000	NH_4	0.001	0.004	0.016	0.005
SD		0.002	0.040	0.001	0.000		0.001	0.004	0.017	0.003
$\bar{X}$	PO_4	0.005	0.002	0.037	0.018	Na	0.639	2.14	1.28	1.56
SD		0.008	0.002	0.033	0.018		0.792	1.61	0.858	1.24
$\bar{X}$	SO_4	0.942	0.776	0.840	0.400	K	0.646	1.01	1.01	1.77
SD		1.23	0.503	0.993	0.309		0.842	0.784	0.638	1.20
$\bar{X}$	Cl	0.802	0.627	0.535	1.62	Ca	6.22	9.45	10.3	7.46
SD		1.04	0.506	0.487	1.49		8.26	7.61	6.59	6.02
						Mg	2.61	0.796	2.45	2.05
							3.51	1.28	1.45	1.28

		$C^{2/}$	$BO^{3/}$	$WT^{4/}$	$CP^{5/}$		C	BO	WT	CP
Low productivity										
$\bar{X}$	NO_3	0.000	0.027	0.397	0.556	NH_4	0.010	0.014	0.011	0.026
SD		0.000	0.060	0.491	0.740		0.016	0.019	0.008	0.048
$\bar{X}$	PO_4	0.009	0.003	0.001	0.002	Na	1.73	1.79	1.19	0.278
SD		0.010	0.003	0.001	0.003		1.63	1.01	0.825	2.22
$\bar{X}$	SO_4	2.96	1.03	0.920	1.28	K	1.39	0.469	0.995	1.78
SD		2.96	0.875	0.779	1.15		1.34	0.337	0.768	1.40
$\bar{X}$	Cl	2.14	0.713	0.760	2.07	Ca	4.20	2.76	4.72	3.94
SD		2.02	0.495	0.634	1.68		4.14	1.87	3.37	2.96
						Mg	1.89	0.754	0.915	1.26
							1.88	0.490	0.695	0.922

[1/] Includes only months during which precipitation occurred (n=8).
[2/] C = Control
[3/] BO = Bole only
[4/] WT = Whole tree
[5/] CP = Complete removal

Table 10--Comparison between harvest and 1-year leaching loss (50-cm) for Douglas-fir and red alder, high and low productivity sites (kg/ha)

	Harvest loss			Leaching loss[1/]		
	N	P	K	N	P	K
Alder high						
Bole only	287	41	150	(136)[2/]	0	(41)
Whole tree	347	47	174	(125)	0	(41)
Complete	966	91	227	(140)	0	(49)
Alder low						
Bole only	311	22	122	(18)	0	(1.2)
Whole tree	378	27	143	(27)	0	2
Complete	885	55	189	(22)	0	(.2)
Douglas-fir high						
Bole only	478	56	225	.2	0	3.6
Whole tree	728	96	207	0	.3	3.6
Complete	949	118	358	0	.1	11.1
Douglas-fir low						
Bole only	161	27	81	.3	0	(9.2)
Whole tree	325	56	140	4.0	0	(4.0)
Complete	526	78	153	5.6	0	3.9

[1/] Losses from control subtracted to derive a net loss value.
[2/] Values in parentheses indicate an apparent net savings to system due to greater losses in controls.

Table 11--Average height and diameter increments (cm) by Douglas-fir seedlings 2 years following establishment

Treatment	Height increment		Diameter increment	
	High site	Low site	High site	Low site
Bole only	26	15	0.54	0.42
Whole tree	28	12	0.52	0.33
Complete removal	24	9	0.51	0.31
Average	26	12	0.52	0.35

Table 12--Mortality of Douglas-fir seedlings 2 years following planting

Treatment		Mortality	% mortality
High-site Douglas-fir			
Bole only	1	12	12
	2	11	11
Whole tree	1	5	5
	2	12	12
Complete	1	8	8
	2	1	1
Average ± Standard Deviation		8.2 ± 4.4	8.5 ± 4.8
Low site Douglas-fir			
Bole only	1	33	35
	2	15	17
Whole tree	1	19	19
	2	37	37
Complete	1	34	34
	2	22	22
Average ± Standard Deviation		26.7 ± 9.1	27.3 ± 9.0

CONCLUSIONS

1. Increasing utilization during harvesting disproportionately increases nutrient losses as compared to the increase in biomass yield.

2. Harvesting the alder sites dramatically reduces leaching, in particular nitrate and bicarbonate leaching at 50-cm soil depth. This reduction in nitrate and Bicarbonate leaching causes a decrease in the leaching of cations.

3. Removal of nutrients during harvesting accounts for nearly all the nutrients lost. Added losses due to leaching are minimal over the first 2 years following harvesting.

4. Growth of Douglas-fir seedlings established on the harvested sites already reflects forest site conditions and the degree of harvesting severity. This is especially true for the low-site Douglas-fir area.

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FORCYTE-10: CALIBRATION DATA AND SIMULATION OF POTENTIAL LONG-TERM EFFECTS OF INTENSIVE FOREST MANAGEMENT ON SITE PRODUCTIVITY, ECONOMIC PERFORMANCE, AND ENERGY BENEFIT/COST RATIO

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ABSTRACT: FORCYTE (FORest nutrient Cycling and Yield Trend Evaluator) is a computer simulation model of forest plant biomass production, litterfall, and decomposition, complete with nutrient cycling, nutrient limitation on growth, and a variety of management interventions. The model is a computerized approach to the estimation of the effects of varying thinning and fertilizer regimes, utilization level, and rotation length on site nutrient budgets, stand productivity, and the economic performance and energy efficiency of management. The model has evolved over 5 years to its present version FORCYTE-10, which is briefly described.

Accompanying the development of FORCYTE, there has been a series of field research projects. Detailed biomass and biogeochemical descriptions of age sequences of Douglas-fir stands on both good and poor sites have been prepared for purposes of model calibration and testing. The present report summarizes some of the results of the FORCYTE-10 field studies on Vancouver Island, British Columbia, and presents some examples of the use of the model when calibrated with these data.

INTRODUCTION

History suggests that we will pass through the present economic downturn and return to a more active economic climate within a few years. With a revitalized world economy, we believe that the trend toward rapid intensification of forest management in order to sustain yields of forest products from a dwindling land base will continue. New uses of forest biomass for energy and chemical feedstock will undoubtedly accompany more conventional uses into the 21st century, further increasing the pressure for intensified biomass production.

Forest managers have traditionally used empirical models to plan timber management and to predict future timber yields. These models have generally been yield tables or computer models of forest growth that have been based on an inventory of biomass that summarizes past growth. For several reasons this type of model has been favored by foresters over the more complex process models that have been produced by forest scientists over the past two decades. Empirical models of the yield table variety are easier, quicker, and cheaper to produce than process

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models and they integrate all of the ecological factors that have influenced tree growth over the rotation as opposed to the small number of factors that are usually simulated in process models. The predictions of future growth based on yield tables will be accurate only if the factors determining biomass production remain unchanged. This is highly unlikely considering the probable future changes in forest management.

By contrast, process models are usually based on the measurement of the processes that determine growth and provide a better basis for predicting future growth under changed conditions. Against this advantage must be set the fact that process models may be more complex to build, the data more difficult and costly to collect, and the model may not include all significant determinants of growth. Also, it is often very difficult to make unrestrained simulation models mimic reality accurately for large, complex ecological systems over the long time periods involved in forest crops.

Yield tables and similar empirical models would be satisfactory for predicting future growth if growth conditions in the future were to remain the same as in the past. We believe, however, that the growing conditions in intensively managed stands of the future will be different from growth in natural unmanaged stands, and we therefore do not think that this traditional approach to yield prediction will be dependable until managed stand yield tables are available for all major future management scenarios. Presently such empirical tables are not available and are unlikely to be so for many years to come, if ever.

Process models would be satisfactory for predicting future growth if they included all major factors influencing production over the rotation, and if it were physically and economically possible to gather enough of the necessary data to make this type of model a practical management tool. To date, process models have tended to remain in the domain of the forest scientist rather than being used by forest managers, in part because of the difficulty of obtaining the necessary input data.

The most pressing present need is for a yield predictor that has the desirable attributes of an empirical model (availability of site- and species-specific data on past growth), but that includes sufficient description of the processes that determine forest growth to give us the type of foresight that is needed in yield prediction under future management conditions. The yield predictions should be accompanied by economic and energy-efficiency predictions, since forestry may be more concerned with maximizing value yield than with maximizing biomass yield.

In response to this perceived need, we have been developing FORCYTE (FORest nutrient Cycling and Yield Trend Evaluator). Starting in 1978, this model has evolved through a variety of development stages to the present version: FORCYTE-10. Reports on earlier versions can be found in Kimmins and Scoullar (1979a, 1979b, 1980, 1982) and Kimmins et al. (1980, 1981a, 1981b). The best description of FORCYTE-10 can be found in Kimmins and Scoullar (1983). This paper will be restricted to a brief description of the model, a description of field research that has been undertaken to provide data for calibration and validation of the 10th version of the model, and will present some of the predictions made by the model calibrated with these data.

BRIEF DESCRIPTION OF FORCYTE-10

FORCYTE-10 is a model of forest plant biomass production, litterfall, and decomposition over a stand cycle (i.e., a rotation) complete with nutrient cycling, nutrient limitation on growth (for one nutrient at a time), and management interventions. It has been designed for even-aged plantation forests that are harvested by clearcutting at or before reaching maturity. The present driving function for plant growth is either site-specific stemwood volume/age equations of the Chapman-Richards type (Piennaar & Turnbull 1973) or simply the site-specific stemwood volume/age data. The predicted growth is modified according to the availability of nutrients to the plants. There is an overall moisture limitation to management-induced growth improvement.

To date, the model has been run only for nitrogen, but any element for which the necessary input data are available can be simulated with little or no modification to the model.

FORCYTE-10 does not simulate the effects of water availability and climate explicitly, but these effects are implicit in the driving-function (site-specific volume/age equations) and, as noted above, there is a simplistic simulation of moisture limitations on improvement of growth by means of fertilization. We recognize that the reliability of the model's predictions will probably be reduced when extremes of climate and moisture are the major constraints on biomass production. The predictions will be most accurate for more moderate environments in which nutrient availability plays a major role in determining tree growth.

FORCYTE-10 consists of two programs (FORCETUP and FORCYCLE) that are run sequentially. FORCETUP is based entirely on empirical field data. It simply describes temporal trends in biomass production, accumulation, and turnover in trees, shrubs, and herbs on sites varying in moisture and fertility status (there is an assumption that poor sites are generally dry and infertile and that good sites are moist and fertile) together with the accompanying dynamics of biomass and nutrients. There is no nutrient feedback on growth and no management intervention. The FORCETUP program simply provides the information required to simulate nutrient-limitation on growth, competition among plants, and the impacts of management practices on plant growth in the

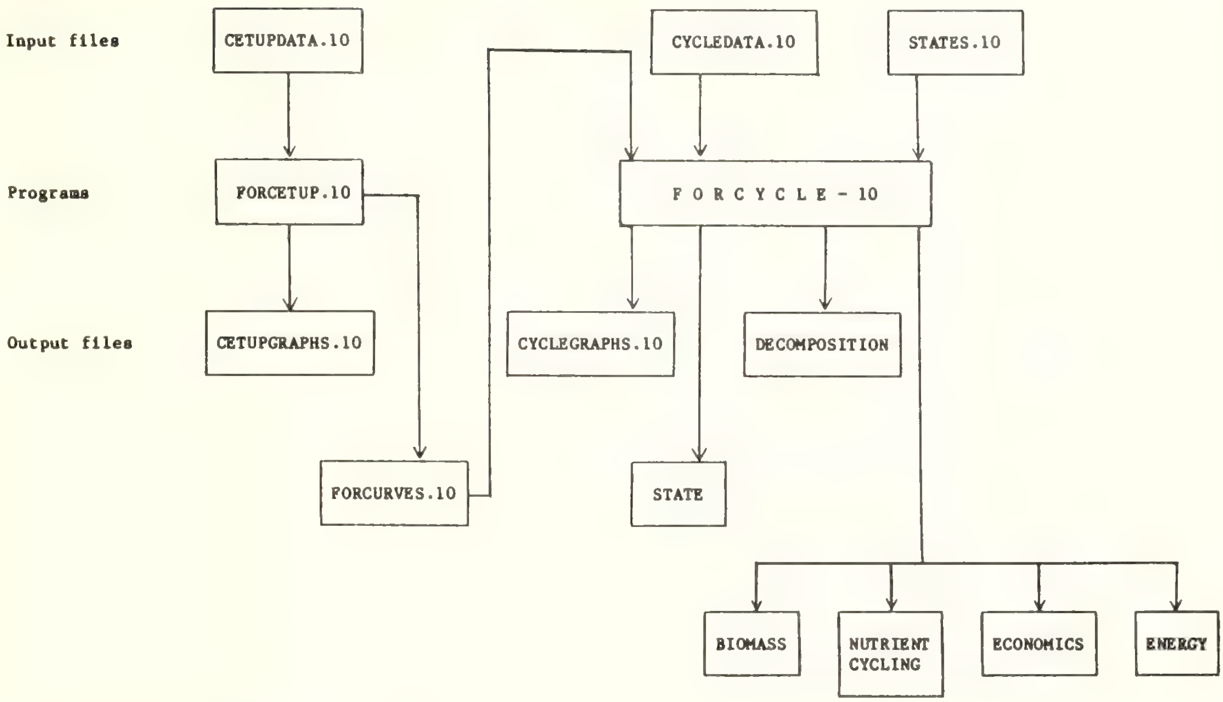


Figure 1a.--Overall structure of FORCYTE-10.

FORCYCLE program. The use of sequential programs enables FORCYTE to be run cheaply and quickly in spite of the complexity of the model. It has enabled us to include much biological detail without making the management simulator (FORCYCLE) excessively complex and costly to run. Both programs are controlled by the user through input data files that permit one to calibrate the model for local conditions.

Details of FORCYTE-10 can be found in Kimmins and Scoullar (1983) and will not be presented here. Figures 1a. and 1b. present the overall model structure and a flow diagram of the compartments and processes described in the model. It has been found that in the short term, the model is relatively sensitive to many ecosystem processes, particularly to changes in forest floor biomass and nutrient content. Over long time periods, however, the model is most sensitive to geochemical inputs and outputs and biological fixation of N.

FIELD STUDIES

Objectives and Design

FORCYTE requires empirical information on the accumulation of plant biomass over time on a variety of site qualities (i.e., traditional yield table information, expanded to include the biomass of stemwood, stembark, branches, foliage, and roots, plus similar data for herbs and shrubs). In addition, data are required on the concentration of the nutrients of interest in, and on the number of age classes of, various biomass components (e.g., how many years of foliage are retained by evergreens; how many annual rings of sapwood are present). For the trees, data are also needed describing the characteristic maximum stand density (stems/ha) as a function of age for each site type.

The objective of the field studies was to provide a minimum set of input data for FORCYTE-10 by documenting the accumulation of biomass and nutrients in an age sequence of Douglas-fir stands growing on a poor site (dry, nutrient-poor, ridge-top site) and on a good site (moist, nutrient-rich, lower-slope site). Various biomass and nutrient transfer pathways were also documented: aboveground litterfall, throughfall, precipitation inputs, and litter decomposition. In addition to data collected to satisfy input requirements, other data were gathered to test the model's predictions. All of the data collected have added to our understanding of the ecosystem, which is facilitating further evaluation of the FORCYTE model.

Designing the field studies involved making an inventory of living biomass and dead organic matter in two age sequences of stands, the ages and other details of which are given in table 1. These stands had a largely unknown and probably variable history of establishment and development. They represented the best age sequences available to us, however, and are probably typical of what might be available to the average user of FORCYTE in North America.

Site Description

Location.--All plots were located within Tree Farm License 20 and Tree Farm 19 of MacMillan Bloedel Industries Ltd. on central Vancouver Island near Port Alberni, British Columbia (latitude 49°14'N., longitude 124°40'W.). The plots were at elevations of 190-500 m with a variety of aspects and slopes (table 1).

Climate.--All plots were characterized by a Cfb climate (Köppen in Trewartha 1968). During the 2 years of study the annual precipitation on the study plots ranged from 1 600 mm to 2 440 mm. Snow occasionally accumulates to depths of 30 cm during the winter months, but rarely remains for more than 6 weeks. The mean annual temperature of the region is about 9°C (Klinka et al. 1979).

Geology and soils.--All plots were underlain by mixed intermediate to basic volcanic bedrock. Soils were Humo-Ferric Podzols (Canada Soil Survey Committee 1978) formed from tills derived from glaciers or outwash materials. They were generally gravelly and coarse textured (sandy loam-loamy sand).

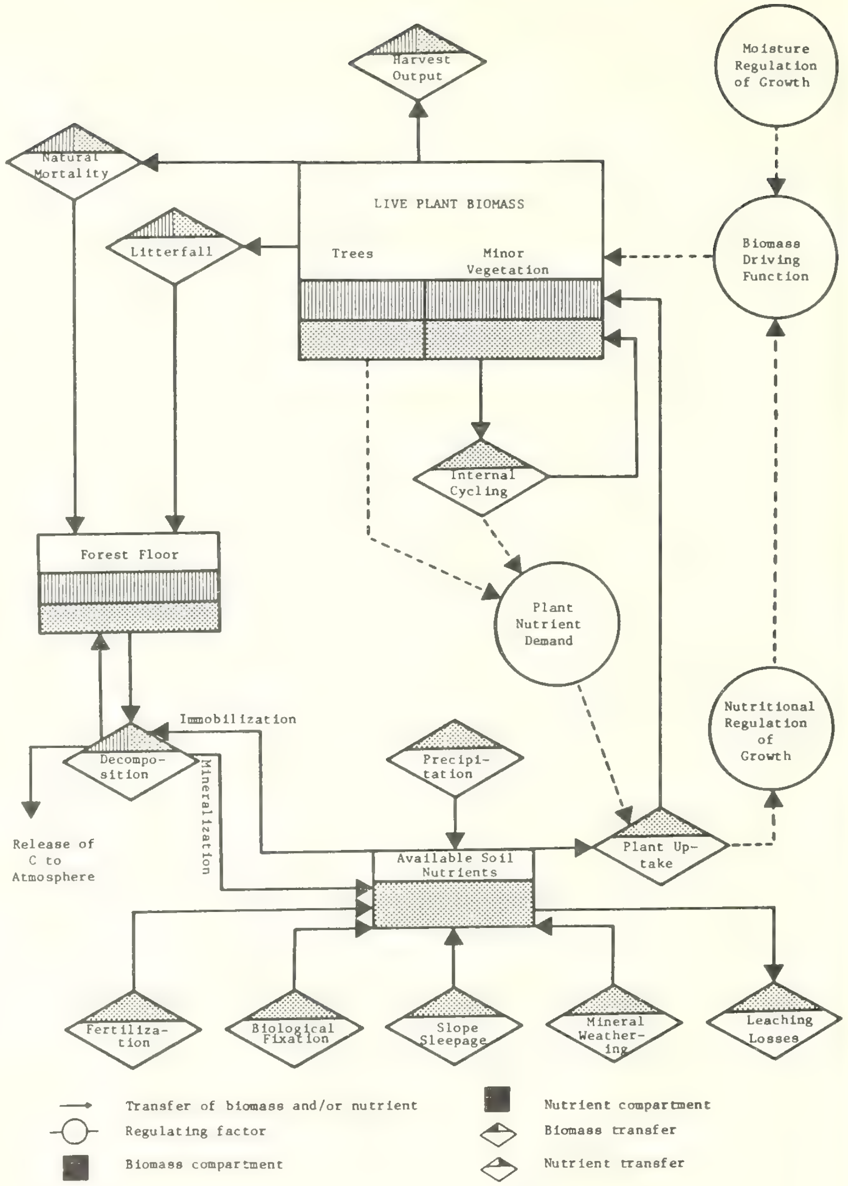


Figure 1b.--Flow diagram of the compartments and processes described in FORCYTE-10.

Table 1--Selected physical characteristics of the study plots

Stand age	Aspect	Slope position	Elevation	Slope
(years)			(m)	
Good sites				
3	NNE	Lower	260	22°
6	NE	Lower	220	26°
11	N	Lower	500	3°
19	NW	Mid-lower	330	5°
48	W	Lower	320	13°
73	NW	Mid-lower	190	3°
Poor sites				
3	SW	Crest	490	10°
5	ENE	Mid	430	4°
9	S	Upper	430	10°
19	NW	Crest	440	2°
48	SSW	Upper	350	15°
74	S	Upper	430	20°

The poor sites were located on rocky ridges where mineral soil occurs only in relatively shallow pockets, 20-40 cm-deep. The good sites were located on lower slopes where the soils are usually greater than 1 m in depth.

Vegetation.--All plots lay in the East Vancouver Island variant of the Drier Maritime Coastal Western Hemlock biogeoclimatic subzone (Klinka et al. 1979). The dominant tree species on all plots was Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco[1] either planted after clear-cutting (on most of the plots) or naturally regenerated after fire (on the 48-, 73-, and 74-year-old plots). These oldest plots also contained some western hemlock (Tsuga heterophylla) and western redcedar (Thuja plicata), with the 48- and 74-year-old plots also containing some red alder (Alnus rubra) trees. The youngest poor plots contained some lodgepole pine (Pinus contorta) seedlings. Characteristics of the dominant trees in the study plots are given in table 2.

Understory vegetation was variable, but the poor plots were generally dominated by salal (Gaultheria shallon) whereas the good plots were generally dominated by swordfern (Polystichum munitum) and herbs, with much fireweed (Epilobium angustifolium) on the youngest plots.

Methods

The good and poor site study plots were selected after 3 months of field inspection on the basis of soil depth, topographic position, presence of indicator plant species, and site index data from the forest cover maps of MacMillan Bloedel. Each plot was approximately 0.5 ha in size.

Field procedures.--

(1) Nutrient Fluxes

(a) Solution transfers

Precipitation and throughfall were collected using simple polyethylene collectors as described by Feller (1977).

The throughfall collectors were randomly located and usually numbered 10 per plot. A total of 18 precipitation and 11 dry fallout collectors were scattered throughout the plots.

(b) Aboveground litterfall

Litterfall was measured using a variety of different sized litter traps for different types of litter. Details of the traps will be given elsewhere (Kimmins et al.[2]). Polystichum munitum litterfall on the good site plots was

Table 2--Characteristics of the dominant trees in the study plots: Number of trees per ha and the average height of the dominant trees

Stand age	No. trees/ha: Douglas-fir	No. trees/ha: Douglas-fir regeneration	No. trees/ha: Other species	Range of heights for dominant Douglas-fir trees
(years)				----(m)----
Good sites				
3	570	1,730	4,950	1.0 - 1.3
6	870	880	1,580	1.3 - 1.5
11	830	680	50	6.0 - 7.0
19	1,230	530	1,170	17.0 - 19.0
48	700	230	200	30.0 - 33.0
73	430	170	300	41.0 - 45.0
Poor sites				
3	1,200	430	0	0.4 - 0.5
5	670	250	180	0.7 - 1.0
9	850	930	310	1.2 - 1.5
19	1,230	3,200	570	7.0 - 8.0
48	1,470	2,000	130	12.0 - 15.0
74	1,570	1,730	500	11.0 - 13.0

[1] All scientific names were taken from Taylor and MacBryde (1977).

[2] J. P. Kimmins et al. Manuscript in preparation, Faculty of Forestry, University of British Columbia, Vancouver, British Columbia, Canada.

determined by removing all dead P. munitum fronds from marked 1-m-square plots, then collecting from these plots any P. munitum fronds that died during the course of the study. Annual litterfall from Epilobium angustifolium on the 3-, 6-, and 11-year-old good site plots was assumed to equal the maximum annual production as measured during understory biomass sampling.

There were 10 overstory and 10 understory litterfall collectors per plot except in the case of P. munitum, for which 5 marked plots were established per study plot.

All solution and litterfall collectors were sampled monthly when solution volumes were recorded, samples of solution were taken for chemical analysis and the collectors emptied and cleaned if necessary. Samples were stored frozen prior to chemical analysis. All litter was removed from the litterfall collectors, placed in labeled paper bags, then dried at 70°C in the laboratory. When dry, litter was sorted into its major components which were then weighed.

(c) Litter decomposition

Litter decomposition was studied using either litter bags or marking techniques. Decomposition was studied for: Douglas-fir needles (all plots), Douglas-fir bark (3 oldest age plots for each site type), Douglas-fir branches greater than 1 cm in diameter (2 oldest age plots for each site type), Douglas-fir branches less than 1 cm in diameter (2 oldest age plots for each site type), Polystichum munitum fronds (all good sites), Gaultheria shallon leaves (all poor sites), and Epilobium angustifolium leaves and stems (3 youngest age good site plots).

All these materials were collected from August through October 1979 as materials about to fall from living vegetation. All the collected materials were dried at 70°C then weighed samples of each were placed in nylon litter bags, except for Douglas-fir twigs and branches which were not placed in bags. These materials were then placed in random locations in the study plots. The time of placement in the plot coincided with the estimated time of maximum litterfall of that material, except for Douglas-fir needles (placed out in November because of collecting difficulties).

After predetermined time intervals (table 6), 5 samples of each litter material were collected per plot. In the laboratory, materials were dried at 70°C, cleaned if necessary, and then reweighed.

Before the litter materials were prepared for placement in the field, samples of each were taken, ground to pass a 20-mesh sieve and analyzed to assess the initial nutrient status of the litter materials, prior to their period of decomposition on the ground.

(2) Nutrient and Biomass Pools

(a) Douglas-fir trees

An inventory of all trees present on the plots was conducted by measuring the height and diameter of each tree, living or dead, present on each of 3 mensuration plots within each plot. Mensuration plots were usually 10 x 10 m in size except for the youngest plots which measured either 20 x 10 or 20 x 20 m.

Several trees adjacent to each of the plots were then destructively sampled for biomass determination. Two classes of tree were distinguished: those less than 2.5 m high on the youngest age plots and those greater than 2.5 m high on the older age plots.

For the youngest age plots (3- and 6-year-old good sites and 3-, 5-, and 9-year-old poor sites), entire trees, including roots, were collected. Regression equations were developed that related the oven-dry (70°C) weights of the stemwood, stembark, needles, roots, and branches to tree height. One set of regression equations was developed for the good sites and another for the poor sites.

For the remainder of the plots with larger trees, selected trees representing the range of sizes (in terms of diameter at breast height (d.b.h.)) present on the plots were felled, then measured and sampled using standard techniques (Kimmins et al.[2/]), to develop regression equations that related the dry weights of stemwood, stembark, needles, live branches and dead branches to functions of d.b.h. outside bark (D) or D^2H where H = height. One set of equations was developed for the good site plots and another set for the poor site plots. The most accurate (on the basis of r^2 and standard error values) regression equations developed are given in table 3. All ln/ln transformed equations have been corrected for logarithmic bias according to the method of Baskerville (1972). A regression equation for root biomass on both rich and poor site plots was obtained from Gholz et al. (1979).

(b) Other tree species

The biomass of western redcedar trees present on the older plots was obtained from regression equations for western redcedar obtained by M. C. Feller[3/]. The biomass of western hemlock and red alder trees on the older plots was obtained using the regression equations

[3/]M. C. Feller. Data on file at Faculty of Forestry, University of British Columbia, Vancouver, British Columbia, Canada.

Table 3--Regression equations relating biomass of tree component to functions of tree height (H) and diameter (D)

Tree component		Regression equation	n	r^2	SE
YOUNG PLOTS (3- and 6-year-old rich sites; 3-, 5-, and 9-year-old poor sites)					
Good sites (H = 80 - 220 cm)					
Stemwood biomass	(BSW)	$\ln BSW = -6.786 + 2.284 \ln H$	10	0.92	0.249
Stembark biomass	(BSB)	$\ln BSB = -4.900 + 1.657 \ln H$	10	.75	.353
Needle biomass	(BN)	$\ln BN = -4.374 + 1.910 \ln H$	10	.75	.391
Branch biomass	(BB)	$\ln BB = -7.821 + 2.486 \ln H$	10	.84	.397
Root biomass	(BR)	$\ln BR = -5.655 + 2.062 \ln H$	10	.79	.392
Poor sites (H = 39 - 171 cm)					
Stemwood biomass	(BSW)	$\ln BSW = -11.132 + 3.231 \ln H$	16	.97	.321
Stembark biomass	(BSB)	$\ln BSB = -10.768 + 2.998 \ln H$	16	.94	.409
Needle biomass	(BN)	$\ln BN = - 9.269 + 3.004 \ln H$	16	.93	.451
Branch biomass	(BB)	$\ln BB = -10.325 + 3.264 \ln H$	16	.83	1.214
Root biomass	(BR)	$\ln BR = -10.833 + 3.228 \ln H$	16	.89	.600
Biomass values are in gms; Heights (H) are in cm.					
OLD PLOTS (11-, 19-, 48-, and 73-year-old rich sites; 19-, 48-, and 74-year-old poor sites)					
Good sites (D = 5 - 56 cm)					
Stemwood biomass	(BSW)	$\ln BSW = -4.041 + 2.900 \ln D$	10	.96	.487
Stembark biomass	(BSB)	$\ln BSB = -5.989 + 2.857 \ln D$	10	.97	.466
Needle biomass	(BN)	$\ln BN = -1.216 + 1.286 \ln D$	10	.96	.216
Live branch biomass	(BLB)	$\ln BLB = -1.453 + 1.575 \ln D$	10	.96	.287
Dead branch biomass	(BDB)	$\ln BDB = -2.517 + 1.554 \ln D$	10	.63	1.034
Poor sites (D = 6 - 29 cm)					
Stemwood biomass	(BSW)	$\ln BSW = -3.988 + 2.928 \ln D$	8	.98	.243
Stembark biomass	(BSB)	$\ln BSB = -5.357 + 2.852 \ln D$	8	.98	.254
Needle biomass	(BN)	$\ln BN = -1.950 + 1.452 \ln D$	8	.87	.334
Live branch biomass	(BLB)	$\ln BLB = -2.791 + 1.910 \ln D$	8	.79	.591
Dead branch biomass	(BDB)	$BDB = 0.152 + 0.810 D^2H$	8	.88	.228
Both site types					
Root biomass	(BR)[1]	$\ln BR \quad -4.696 + 2.693 \ln D$	26	.96	.356

Biomass values are in kg; Diameters (D) are in cm; D^2H values are for both D and H in meters.

All equations were significant at P<.01. n is the sample size, r^2 is the coefficient of determination and SE is the standard error of the estimate of the dependent variable and is in ln units when the regression equation is logarithmic.

1/ Taken from Gholz et al. (1979).

given by Gholz et al. (1979) and, in the case of western hemlock roots (no regression equation given) assuming that roots comprised 20 percent of the total tree biomass.

(c) Understory plants

Understory biomass was determined by clipping at ground level all plants present in a 1-m^2 sample plot, with 10 randomly located sample plots per plot. The material from each sample plot was oven dried at 70°C then sorted into major components which were weighed separately.

Root biomass was determined by collecting the aboveground and belowground parts of individual plants, oven drying these at 70°C and measuring the aboveground/belowground (A/B) dry weight ratios for replicate samples (5 to 10) of each understory component over the range of plots on which that component was important. Mosses and lichens were taken to have no root biomass.

(d) Forest floor

Forest floor materials were collected from 25- x 25-cm sample plots after first removing all living aboveground vegetation. There were 10 sample plots per plot. The L layer was first removed and placed into a labeled bag, followed by the F and H layers if present. All living roots greater than 0.2 cm in diameter were removed prior to oven drying at 70°C. Samples were then weighed, ground to pass a 20-mesh sieve, and stored prior to chemical analysis.

(e) Mineral soil

Small soil pits were dug, 10 per plot, and samples of the 0- to 20- and 20- to 50-cm layers of mineral soil were taken for analysis. Each layer sampled was analyzed for bulk density, percent of coarse fragments and chemical properties using standard methods (Kimmins et al.2/).

Laboratory procedures.--All oven-dried (70°C) and ground samples of plant material were analyzed for N, P, K, Mg, and Ca, but only N results are presented in this report.

Nitrogen in mineral soil and in ground plant material samples was determined by standard Kjeldahl digestion. Ammonium concentrations in solution were measured using a standard colorimetric method on a Technicon Autoanalyzer, as described in Feller (1977).

Nitrogen in throughfall was measured as nitrate, ammonium, and total Kjeldahl nitrogen. Nitrate and ammonium were measured using standard colorimetric methods on a Technicon Autoanalyzer, as described in Feller (1977). Total Kjeldahl nitrogen was determined following a semi-micro-Kjeldahl digestion of the solution similar to that described by Greenberg et al. (1981). The resulting ammonium was determined using the Technicon Autoanalyzer.

Soil organic matter content was determined by dry combustion (500°C for 1 hour). This was converted to organic C by dividing by a factor of 1.8.

RESULTS AND DISCUSSION

A summary of the results is given in figures 2 to 6 and tables 5 to 7. When interpreting the field data it is necessary to keep two points in mind.

First, because of various constraints there was no replication of plots within each age class. Variation between stands of the same age on the same site may be substantial, but is currently unknown for our study area. Preliminary data, however, suggest that for at least one plot variation can be substantial. Inspection of figures 2 to 6 suggests that the 74-year-old poor plot might be anomalous. In comparison to the 48-year-old poor plot, the 74-year-old plot had a greater amount of rock outcrops (15 percent vs. 5 percent) and shallower soils (table 5). The Douglas-fir trees on the 74-year-old plot were slightly lower (table 2) and covered less of the area than the trees on the 48-year-old plot (63 percent vs. 77 percent). Preliminary assessment of another nearby 74-year-old poor plot indicates that this plot, in comparison to the existing 74-year-old plot, generally had taller trees with a greater biomass and an understory composition more similar to that of the 48-year-old plot. The nature of the soil appears to be a major determinant of variability in this case. For the biogeoclimatic zone in which our study plots lay, Courtin et al. (1983) reported that good site soils had greater lateral variability than poor site soils, but they did not assess the corresponding variability in vegetation. The question of within-plot variability will be addressed in the future development of FORCYTE.

Second, the data points for the two chronosequences, as shown in figures 2 to 6, are joined by straight lines. It is unlikely that a real stand would follow such disjointed trajectories. Because of our current uncertainty over within-plot variability, however, we are unable to plot in smooth curves, or lines of "best fit", which we consider most accurate. For the present it seems most appropriate to join the data points by straight lines. This is somewhat unrealistic, but future work should delineate more accurate, smoother curves.

Figures 2 to 6 indicate how the distribution of organic matter and its nitrogen content change with age and how this distribution differs between the two site types. Beginning at about age 10 for the good sites and age 20 for the poor sites, Douglas-fir trees constitute the dominant biomass and organic matter-nitrogen pool (fig. 2).

For the younger good site plots (age 3 and 6 years) and the younger poor site plots (age 3, 5, and 9 years) the understory contains most of the ecosystem biomass-N. This is similar to results reported by Switzer and Nelson (1972) for loblolly pine forests in Mississippi and by MacLean and Wein (1977a, 1977b, 1978b) for jack pine forests in New Brunswick. Turner (1975) has also obtained similar data for an age sequence of Douglas-fir stands in western Washington. None of these studies presented data for different site types. The understory is relatively more important, both as a biomass and as a N pool, on the poor than on the good sites. Standing dead Douglas-fir trees are also relatively more important, both as a biomass and as a N pool on the poor than on the good sites for the 48- and 73- to 74-year-old plots.

Figures 3 to 6 present more detailed data on the major ecosystem components given in figure 2. The distribution of biomass and its N content for the Douglas-fir trees is given in figure 3. For the good sites, biomass accumulation in trees has continued throughout the age sequence whereas for the poor sites, biomass has apparently leveled out around age 50. This trend in the poor sites is likely to be an artifact caused by an anomalous 74-year-old plot, as discussed above. For both site types, stemwood comprised most of the biomass followed by roots, then bark. Needles comprised a greater proportion of the biomass on the 48- and 73- to 74-year-old plots for the poor site type than for the rich site type.

The differences in the relative importance of different tree components may be partly associated with the different stand densities (table 2), but they are probably also associated with the different ways in which the trees distribute biomass according to site type. This can be seen from simple calculations using the derived biomass regression equations (table 4). The regressions suggest that when the Douglas-fir trees on good sites were young, stemwood, needles and roots had relatively greater biomass, and branches relatively less biomass, than Douglas-fir trees on poor sites. When the trees were older, needles, live branches, and dead branches had relatively greater biomass, and stemwood and

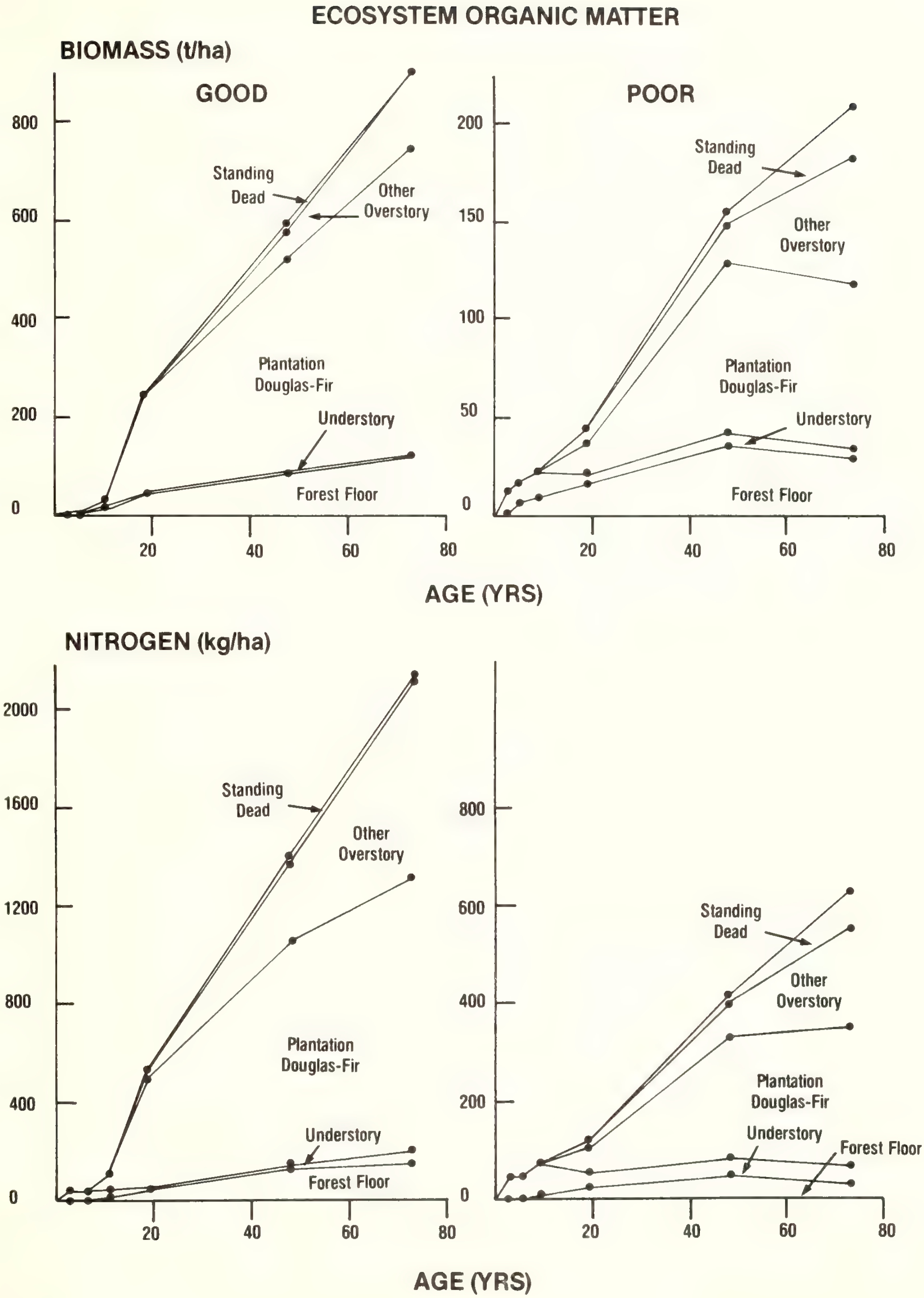


Figure 2.--Biomass and nitrogen distribution among the major components of the studied Douglas-fir stands.

Figure 3.

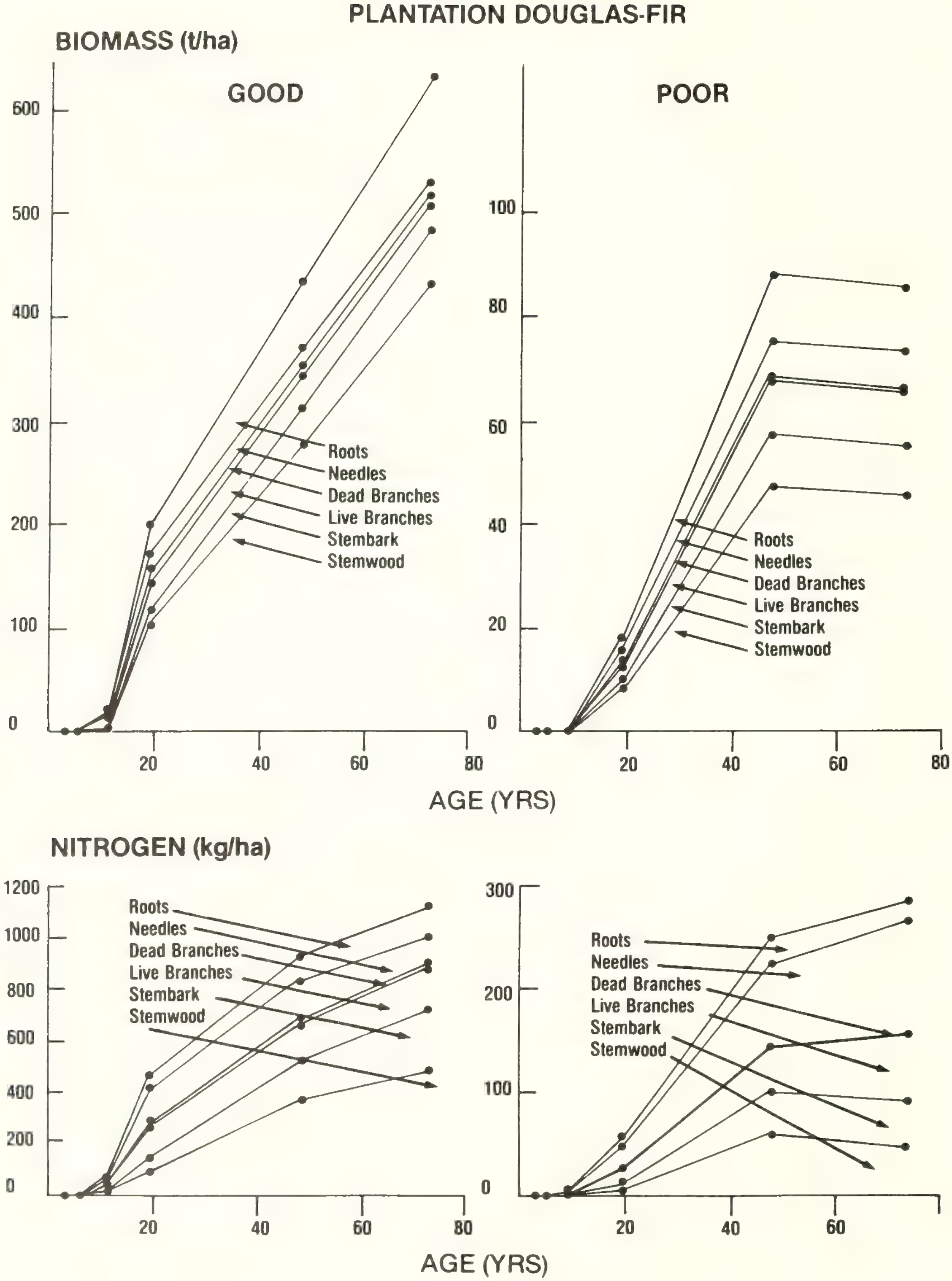


Figure 3.--Biomass and nitrogen distribution among the major components of the plantation Douglas-fir trees in the studied stands.

Figure 4.

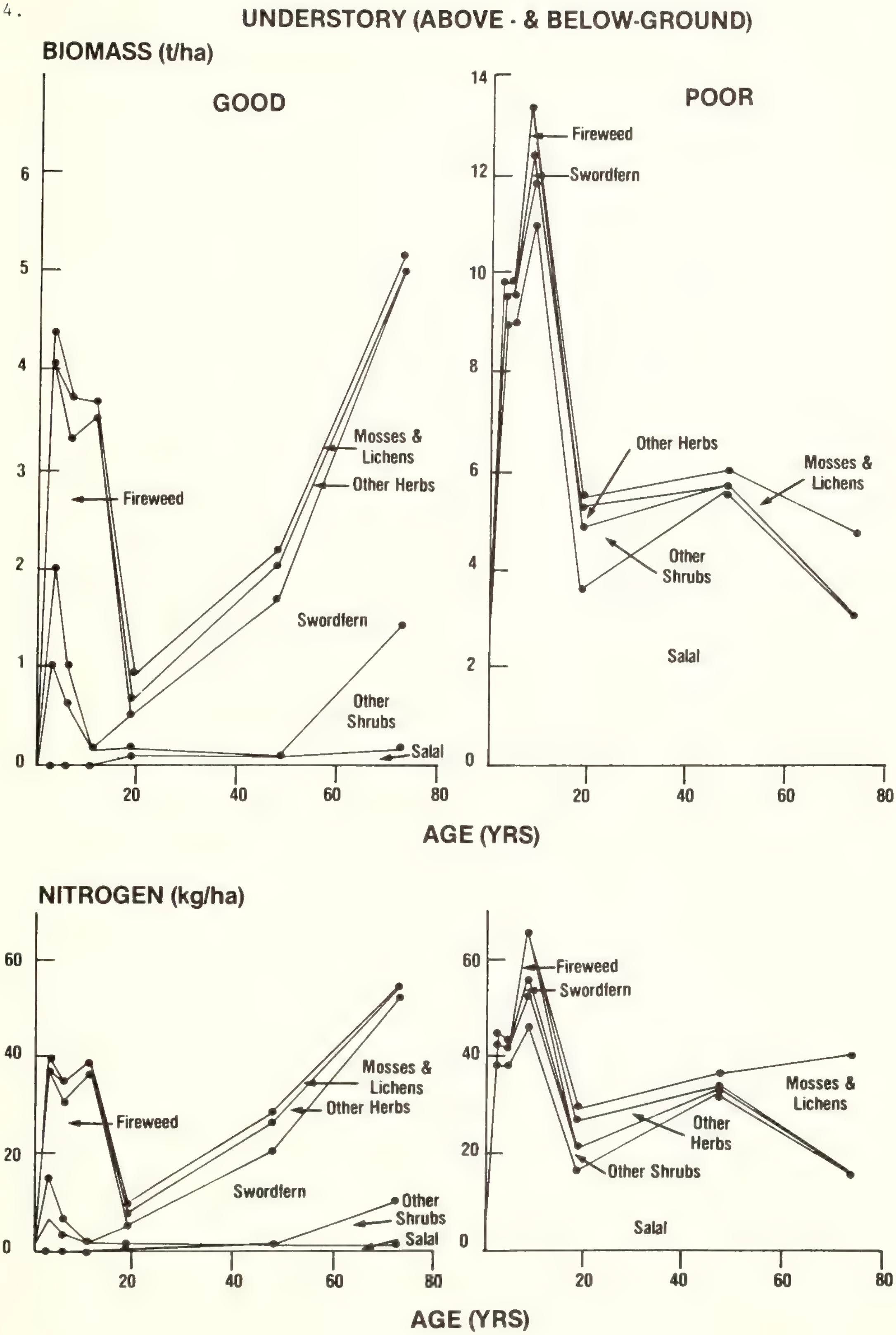


Figure 4.--Biomass and nitrogen distribution among the major understory components of the studied Douglas-fir stands.

Figure 5.

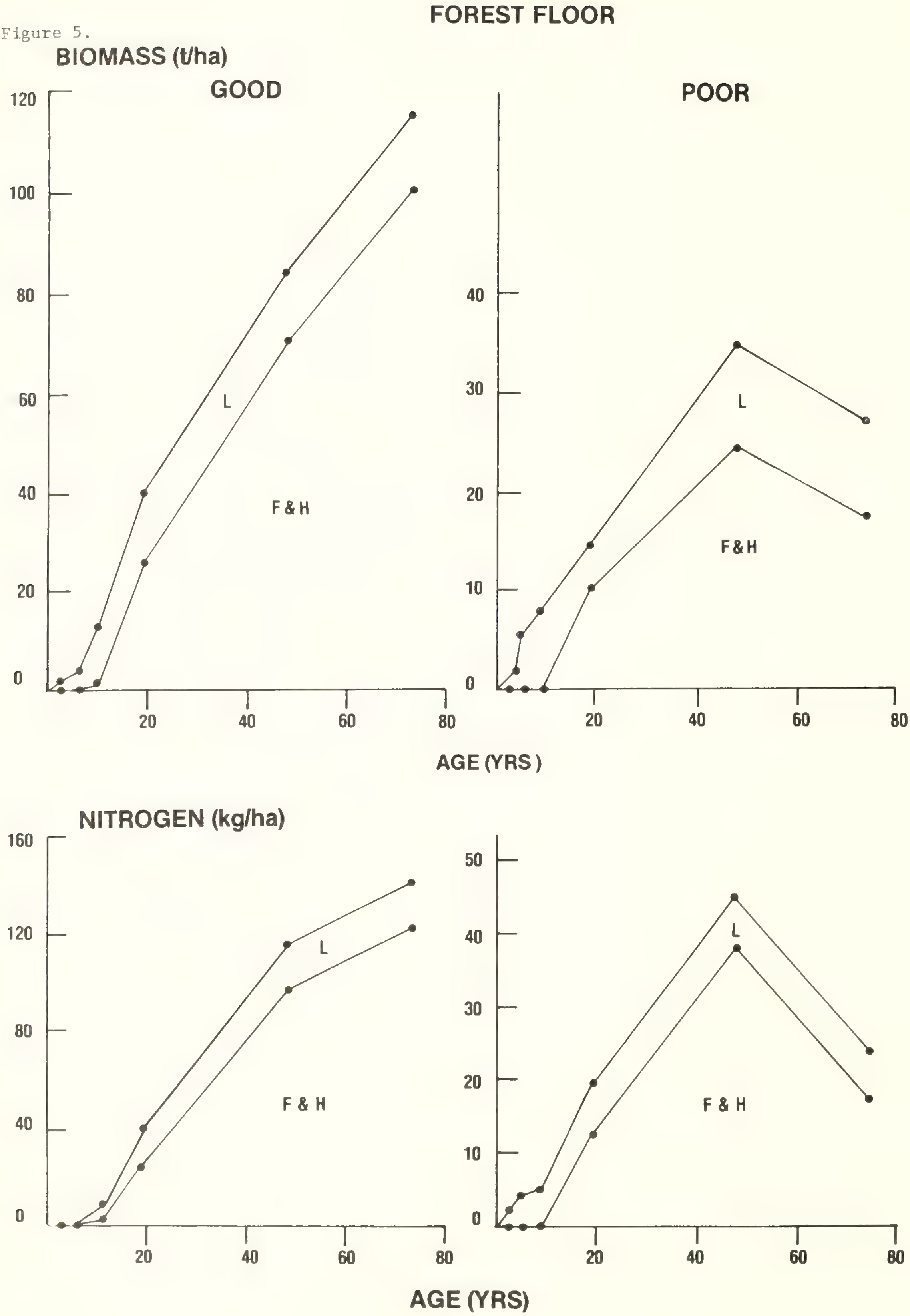
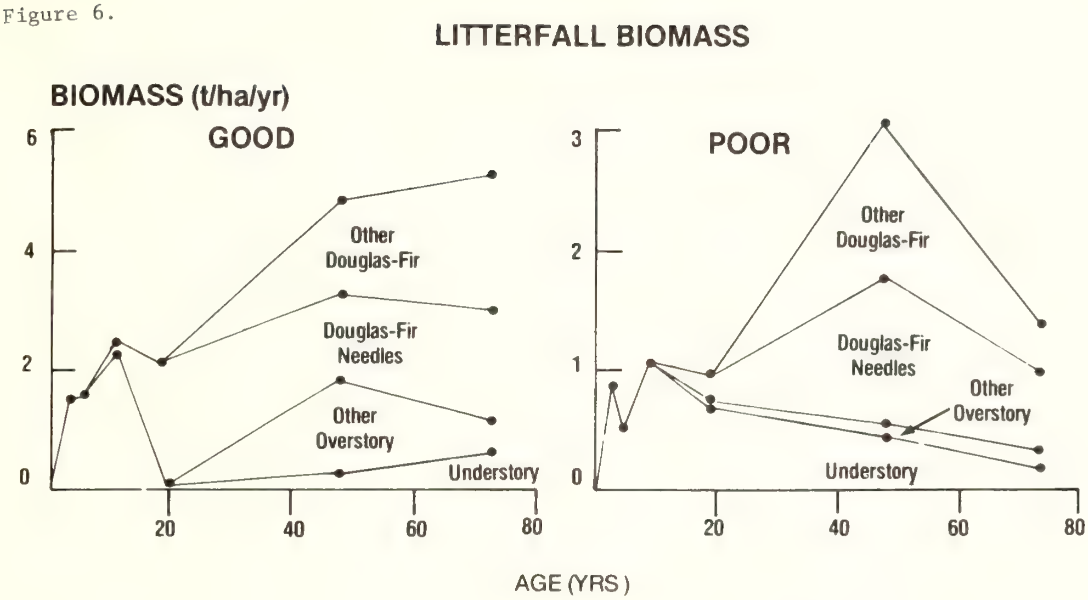


Figure 5.--Biomass and nitrogen content of the litter (L) and partially decomposed F&H layers of the forest floors in the studied Douglas-fir stands.

Figure 6.



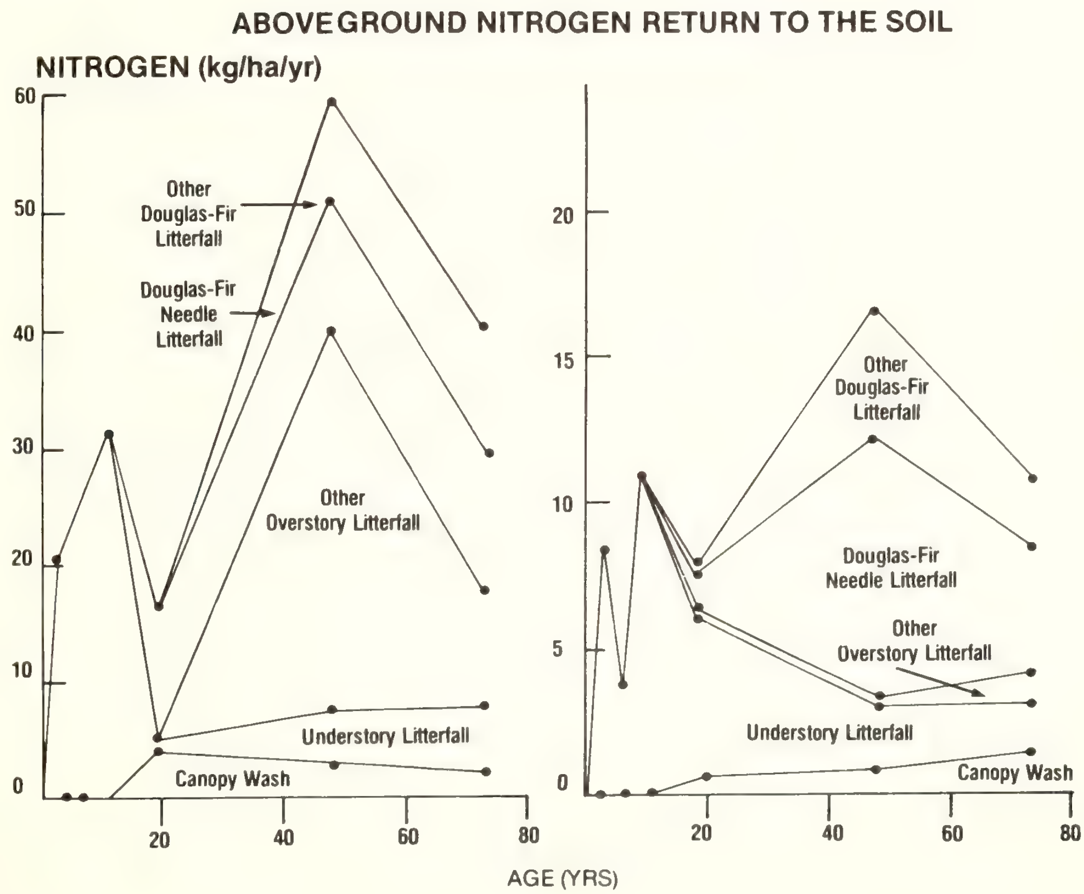


Figure 6.--Mean annual boimass of the major litterfall components in the studied Douglas-fir stands; and mean annual aboveground nitrogen return to the soil by means of canopy wash as well as by means of the major litterfall components.

Table 4--Percentage distribution of biomass among the different components of Douglas-fir for young trees and old trees on both rich and poor sites

	Stemwood	Stembark	% needles	Live branches	Dead branches	Roots
YOUNG TREES						
Good Sites - ht = 80 cm	18	8	39	15	0	21
160 cm	20	6	34	20	0	20
Poor Sites - ht = 80 cm	13	7	30	33	0	17
160 cm	13	6	27	36	0	18
OLD TREES[1/]						
Good Sites - d.b.h. = 10 cm	42	5	17	27	9	--
= 25 cm	68	8	6	13	4	--
Poor Sites - d.b.h. = 10 cm (ht = 7 m)	55	12	14	18	1	--
25 cm (ht = 20 m)	72	14	5	9	0	--

Biomass values were calculated using the regression equations given in table 3.

1/ For old trees, roots were omitted so the percentage values refer to percentage of total aboveground biomass.

stembark had relatively less biomass on good sites than on poor sites.

Nitrogen accumulation in the biomass continued throughout the age sequence for both good and poor sites, although at a rate that decreases with time after age 11 for the good sites and age 19 for the poor sites. After age 19, stemwood was the single most important storage compartment for N in the good sites, whereas foliage was the most important in the poor sites. This was partly because of the relatively greater contribution of needles to the total tree biomass in the poor sites (age 48 and 73 to 74 years), but also because of the significantly (P less than 0.05) higher concentrations of N found in the poor site needles compared to the good site needles (1.26 percent versus 1.09 percent respectively; average of the two oldest plots for each site type). This may suggest that it is not N that is causing the difference in productivity between the good sites and the poor sites, but rather some other factor or factors such as soil moisture.

Trends in understory biomass were markedly different between the good and poor sites (fig. 4). The understory biomass on good sites was dominated by fireweed (Epilobium angustifolium) up to age 11. Canopy closure occurred between ages 11 and 19. From age 19 onward, swordfern (Polystichum munitum) dominated with shrubs becoming important at age 73. The total understory biomass showed a peak around ages 3-6, followed by a sharp decline just after canopy closure, followed by a steady increase with age with maximum values being found for the oldest (age 73) plot studied.

The poor site understory was dominated throughout the age sequence by salal (Gaultheria shallon) with mosses and lichens increasing in importance with time. Total understory biomass peaked around age 9 and thereafter tended to decline with age.

The distribution of N in the understory tended to closely follow the distribution of biomass. The only difference was that in the oldest poor plot, mosses and lichens contained most of the understory N. This may also be an artifact caused by an anomalous plot, as discussed earlier.

The forest floor biomass was dominated by fresh litter (L layer) until around age 10 (fig. 5). Thereafter, partially decomposed F and H layers dominated. Forest floor biomass continued to increase through the age sequence for the good sites, but appeared to level off or decline after age 48 for the poor sites. Again, this may be an artifact caused by an anomalous plot. Nitrogen distribution in the forest floor followed identical trends to those of the biomass. Similar results were found by Turner (1975) for Douglas-fir stands in western Washington.

Table 5--Nitrogen quantities in the mineral soil to rooting depth, which is assumed to be 1 m in the rich sites.

Stand age	Soil depth	Total N	C:N[1]
(years)	(m)	(kg/ha)	
Good sites			
3	1.0	4,970	44
6	1.0	3,710	45
11	1.0	5,490	38
19	1.0	4,390	37
48	1.0	13,090	29
73	1.0	5,710	25
Poor sites			
3	0.3	1,530	58
5	0.4	2,270	79
9	0.4	4,440	53
19	0.3	2,890	45
48	0.3	2,250	42
74	0.2	3,990	27

1/ In surface 20 cm of mineral soil.

Aboveground return of litter and nitrogen to the soil is given in figure 6. Litterfall biomass increased with age for the good sites, both for Douglas-fir and for total litterfall, although understory litterfall peaked during the period prior to canopy closure. For the poor sites, litterfall biomass appeared to peak around age 48. The age 48 plots were affected by considerable windthrow during the second year of the study, however, and the 74-year-old poor plot may be anomalous. Total Douglas-fir litterfall in the 48-year-old poor plot was 1 280 kg/ha/yr during year 1 and 3 660 kg/ha/yr during year 2. In the absence of this windthrow, total litterfall in the 48-year-old poor plot would have been similar to that in the 74-year-old poor plot.

Aboveground N return to the soil can be via solution (canopy wash) or via litterfall. Canopy wash was considered to be the difference between total dissolved N in throughfall and that in precipitation. It accounted for a negligible proportion of the aboveground return of N in the youngest age plots (3-11 years) and never more than 25 percent of the total aboveground return in any of the other plots.

Litterfall accounted for most of the aboveground return of N to the soil. Trends in litterfall N content paralleled trends in litterfall biomass with the exception of "other overstory" litterfall in the two oldest good site plots. This was a relatively greater source of N than its biomass suggested. This is because most of the "other overstory" in these two plots was red alder, which had relatively high concentrations of N in its tissues and litter.

Turner (1975) and Gessel and Turner (1976) reported that N and organic matter return to the soil in litterfall in Douglas-fir stands became fairly constant after about age 20. This does not appear to be the case for our good sites although it may be the case for our poor sites. The magnitude of annual litterfall biomass and its N content are similar to those reported by Turner (1975) and Gessel and Turner (1976). MacLean and Wein (1978a) reported that litterfall biomass in their jack pine stands became fairly constant after about age 30, but that N content of litterfall tended to increase somewhat.

The total N content of the mineral soils showed no consistent trends with age (table 5). MacLean and Wein (1977a, 1978b) reported similar results for their jack pine stands. They attributed this variability to differences in fire history between their different sampling sites. This may also be the case for the Vancouver Island plots. It might also be partly due to the inherently high variability in the physical and chemical properties of these soils that could overwhelm any relatively minor changes caused by changes in vegetation age (Courtin et al. 1983).

The data in table 5 do suggest, however, that the good sites had greater quantities of N in their mineral soils than did the poor sites. The good sites also tended to have lower C:N ratios than the poor sites. On both sites, C:N ratios tended to decrease with age of the stand, suggesting that ecological processes depending on stand age did have some influence on the surface soil chemistry.

Table 6--Rates of mass loss from decomposing litter materials in the study plots

Litter material/plot	Percentage loss of biomass after:					
	1 mo.	3 mo.	6 mo.	9 mo.	12 mo.	24 mo.
Douglas-fir needles						
Good sites - 3 years	16.4	20.1	22.2	22.8	22.6	35.7
- 6 years	16.7	19.0	19.8	21.7	21.5	38.2
- 11 years	14.8	17.9	21.5	22.3	23.1	48.5
- 19 years	15.0	19.5	22.5	26.0	31.9	47.0
- 48 years	15.5	21.2	23.9	26.7	31.1	46.0
- 73 years	13.9	20.9	22.3	25.5	26.5	42.8
Poor sites - 3 years	13.0	16.7	18.7	20.6	21.2	37.2
- 5 years	11.6	17.6	18.5	19.6	21.3	37.6
- 9 years	11.0	16.8	16.7	18.3	22.6	39.1
- 19 years	11.3	16.5	18.3	20.5	24.2	42.5
- 48 years	12.2	17.5	19.8	21.4	25.8	50.0
- 74 years	10.2	17.4	22.2	22.4	26.9	51.0
Douglas-fir bark						
Good sites - 19 years	1.7	4.6	6.2	3.4	5.4	6.4
- 48 years	1.3	3.3	4.5	3.7	3.7	8.9
- 73 years	1.6	3.3	3.9	2.9	3.2	6.4
Poor sites - 19 years	0.5	3.5	4.8	7.3	7.0	7.1
- 48 years	0.5	3.3	5.3	4.8	5.5	10.3
- 74 years	2.7	3.7	6.3	6.0	8.6	11.0
Douglas-fir branches greater than 1 cm diameter						
Good sites - 48 years	-	6.9	6.0	3.7	2.8	9.0
- 73 years	-	6.9	6.2	3.8	2.8	8.2
Poor sites - 48 years	-	6.4	6.3	4.8	2.6	8.1
- 74 years	-	6.4	5.7	5.4	3.6	9.7
Douglas-fir branches less than 1 cm diameter						
Good sites - 48 years	-	4.7	9.3	8.5	8.4	14.0
- 73 years	-	5.2	7.3	5.7	9.4	11.8
Poor sites - 48 years	-	2.3	5.8	4.5	5.7	11.0
- 74 years	-	2.3	4.9	4.9	9.0	12.7
Swordfern fronds						
Good sites - 3 years	8.6	14.1	15.4	17.7	20.1	26.2
- 6 years	6.1	14.3	13.5	16.8	23.1	31.4
- 11 years	6.3	9.7	13.1	12.9	11.8	16.5
- 19 years	6.7	12.2	14.2	12.0	13.8	18.7
- 48 years	7.8	11.8	15.8	13.3	11.7	19.4
- 73 years	4.7	10.5	11.9	11.8	12.0	25.3
Salal leaves						
Poor sites - 3 years	10.5	19.0	21.5	20.6	20.5	42.0
- 5 years	9.2	14.3	20.9	21.4	24.3	49.2
- 9 years	7.9	11.7	19.3	24.2	28.6	38.5
- 19 years	7.6	13.6	20.1	22.3	28.1	58.7
- 48 years	10.5	15.2	23.6	21.3	29.3	53.1
- 74 years	12.0	15.1	23.1	21.9	35.1	49.3
Fireweed stems						
Good sites - 3 years	3.2	6.2	5.7	14.4	19.9	39.1
- 6 years	5.0	5.4	3.0	9.0	16.2	33.3
- 11 years	5.2	5.6	5.7	9.0	17.6	33.5

Table 6-- cont.

Litter material/plot	Percentage loss of biomass after:					
	1 mo.	2 mo.	4 mo.	6 mo.	9 mo.	12 mo.
Fireweed leaves						
Good sites - 3 years	27.9	30.0	36.1	47.4	54.4	64.2
- 6 years	22.7	27.4	33.7	41.3	49.2	57.9
- 11 years	22.9	23.9	38.3	39.1	43.4	57.8

The rate of mass loss from decomposing litter materials is given in table 6. Of all the materials studied, fireweed leaves exhibited the greatest rates of decomposition, losing about 60 percent of their initial mass after 12 months. Douglas-fir bark and Douglas-fir branches greater than 1-cm diameter exhibited the lowest rates of decomposition, losing about 8-10 percent of their initial mass after 24 months. For Douglas-fir needles, there is some indication that decomposition rates increased with increasing stand age. This is also the case for salal leaves, but not for swordfern fronds.

Edmonds (1979) also studied the rates of decomposition of Douglas-fir needles in an age sequence of stands. The biomass decomposition rates he reported were greater than those found in the present study. Edmonds (1979) also found no clear trends in decomposition rates with stand age for stands aged from 11 to 97 years. He did find that decomposition rates were greatest where temperature and moisture conditions were most favorable and that low litter moisture inhibited decomposition in summer. Litter in the youngest age plots in the present study was most vulnerable to dehydration in summer, but moist microsites in the youngest age plots did exist, which could account for the trends discussed above. MacLean and Wein (1978c) also reported no consistent trends in rates of litter decomposition with stand age in their jack pine stands.

The changes in the N content accompanying the decomposition of the litter materials are given in table 7. Few consistent trends are apparent. After being placed on the forest floor, decomposing litter materials usually gained N although some did not. In addition, a given Douglas-fir litter material usually gained more N on the good sites than on the poor sites. For any given litter material in any plot, the trend in N content with duration of decomposition was extremely variable and only an occasional consistent trend was seen. Edmonds (1979) reported similar variable results from the N content of decomposing needles in an age sequence of Douglas-fir stands.

TYPE OF OUTPUT FROM FORCYTE-10

FORCYTE provides a variety of types of output. Most of these are intended to provide the user with a detailed understanding of the simulated annual changes in various parameters and processes in the simulated forest on which the predictions are based. This is important in order to give the user confidence in the biological realism of the model and its predictions. Values of up to 120 parameters can be printed out annually in a series of 12 graphs for runs of up to 500 years although use of the model for much more than 200 years is questionable. Two diagnostic files can also be printed out if desired. One of these describes the biomass and nutrient content of every live and dead plant component in the model at the end of each run and the other presents details of the annual net immobilization or mineralization of the simulated nutrient from each of the decomposing plant components identified in the forest floor. The user is advised to carefully inspect this diagnostic output before examining the model's predictions. Finally, the model prints a series of tables summarizing the predicted biomass and nutrient budgets for the entire run, for each rotation in the run, and for each thinning or fertilization event within the rotation. FORCYTE-10 also has the ability to perform an economic analysis of the management scenario being simulated, as well as an energy input/output evaluation.

As an illustration of the potential use of the model, figures 7, 8 and 9 show the results of a series of simulations using the calibrated FORCYTE-10 for a British Columbia, west coast Douglas-fir forest growing on a medium site in which rotation length, biomass utilization level, and intensity of management were varied. Figure 7 shows that the total tree biomass harvested over the 180-year period increases as the intensity of management increases. The total stemwood biomass harvested shows an identical trend, except for the situation of whole-tree harvesting on 60-year rotations, in which case no difference occurs as the intensity of management increases from case 1 to case 2. Stemwood biomass yield over the period is increased by going from 90- to 60-year rotations, but is less with the 30-year than with the 60-year rotations. Whole-tree harvesting, as compared to stems-only

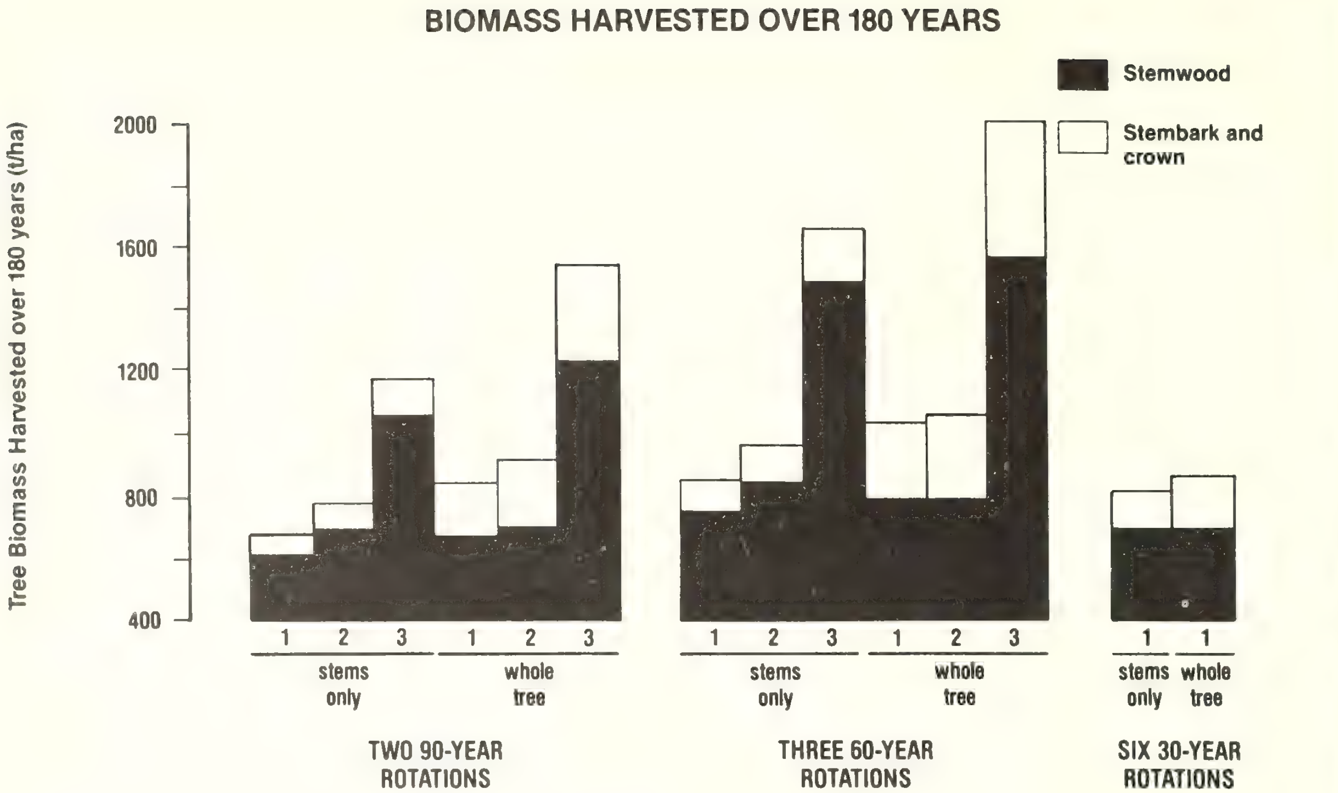


Figure 7.--Summary of simulated mean annual harvested biomass for Douglas-fir growing on a medium quality site in coastal British Columbia over a 180-year period. The simulations involve:

(1) three different intensities of management (a) precommercial spacing at age 15 + final harvest, (b) the spacing + two 30 percent thinnings at ages 30 and 45 + harvest, and (c) the spacing + the 2 thinnings + 3 fertilizer applications of 225 kg/ha at ages 16 and 46.

(2) two different intensities of utilization (stems-only and whole-tree harvests.

(3) three different rotation lengths (90 years, 60 years and 30 years).

The shaded area of the graph indicates stemwood biomass; the unshaded portion indicates stembark and crown biomass.

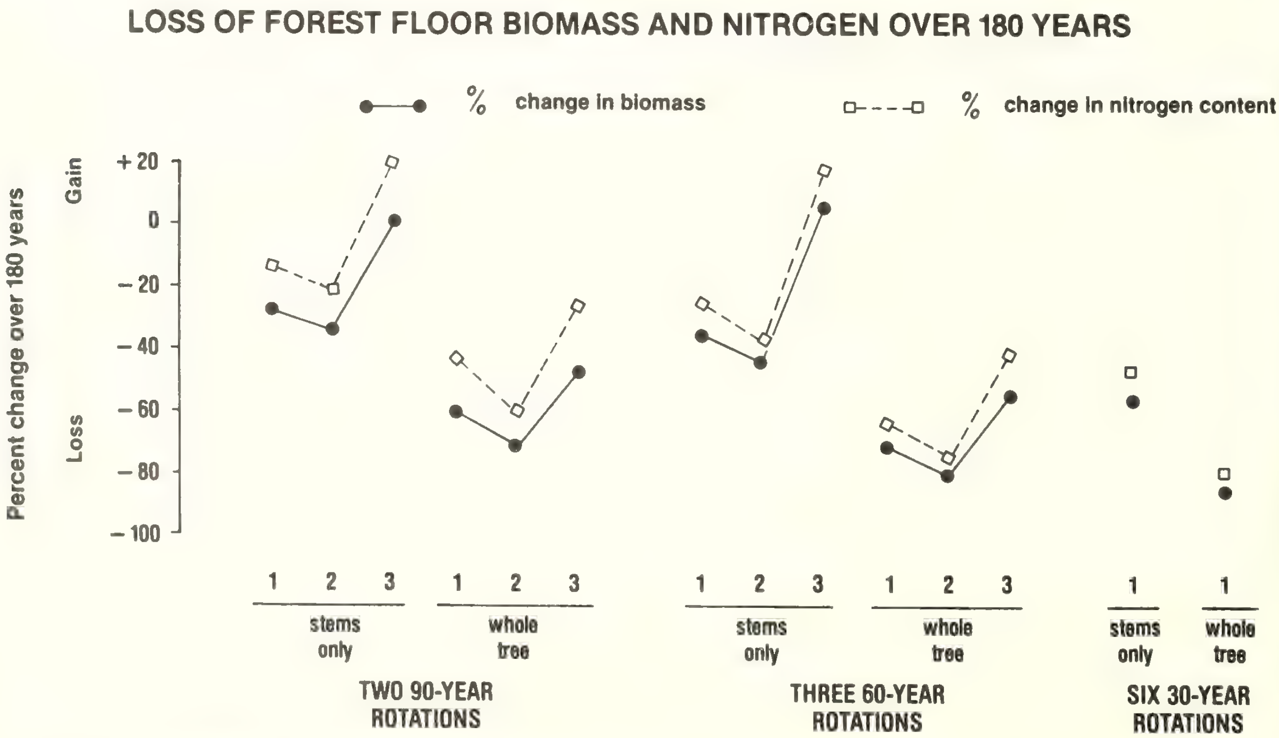


Figure 8.--Summary of the simulated changes in forest floor biomass and nitrogen content under the management and harvesting regimes described in figure 7.

Table 7--Percentage of the original nitrogen content of litter materials remaining after various periods of decomposition

Litter material/plot	Percentage remaining after:					
	1 mo.	3 mo.	6 mo.	9 mo.	12 mo.	24 mo.
Douglas-fir needles						
Good sites - 3 years	107	121	106	126	104	160
- 6 years	101	114	121	102	106	142
- 11 years	103	102	105	115	106	120
- 19 years	96	97	113	127	104	136
- 48 years	115	126	128	112	142	134
- 73 years	112	137	125	143	142	103
Poor sites - 3 years	109	93	117	117	87	93
- 5 years	109	107	100	99	93	105
- 9 years	107	100	101	107	96	97
- 19 years	91	88	101	102	110	122
- 48 years	98	96	103	102	111	132
- 74 years	109	108	108	113	121	102
Douglas-fir bark						
Good sites - 19 years	111	118	114	115	129	128
- 48 years	103	119	116	123	133	154
- 73 years	100	120	122	129	129	120
Poor sites - 19 years	86	104	97	102	95	107
- 48 years	105	107	108	104	97	99
- 74 years	81	100	88	109	90	98
Douglas-fir branches greater than 1 cm diameter						
Good sites - 48 years	-	110	143	155	165	164
- 73 years	-	108	141	144	166	141
Poor sites - 48 years	-	126	139	141	132	109
- 74 years	-	109	126	146	137	124
Douglas-fir branches less than 1 cm diameter						
Good sites - 48 years	-	110	104	105	97	108
- 73 years	-	120	106	106	87	91
Poor sites - 48 years	-	87	85	85	89	85
- 74 years	-	90	100	108	87	93
Swordfern fronds						
Good sites - 3 years	88	93	86	89	88	110
- 6 years	86	90	93	89	100	105
- 11 years	93	90	93	86	89	120
- 19 years	100	89	93	97	97	114
- 48 years	94	93	107	111	112	120
- 73 years	99	100	109	106	111	118
Salal leaves						
Poor sites - 3 years	108	91	103	111	115	87
- 5 years	91	83	93	91	90	92
- 9 years	114	119	101	96	118	105
- 19 years	113	115	108	113	120	88
- 48 years	97	117	109	119	121	83
- 74 years	107	114	106	107	100	97
Fireweed stems						
Good sites - 3 years	110	110	113	118	115	116
- 6 years	109	106	107	113	113	120
- 11 years	104	103	103	108	110	108

Table 7-- cont.

Litter material/plot	Percentage remaining after:					
	1 mo.	2 mo.	4 mo.	6 mo.	9 mo.	12 mo.
Fireweed leaves						
Good sites - 3 years	107	103	115	126	121	95
- 6 years	110	108	111	108	112	97
- 11 years	101	110	111	113	116	92

harvesting, produces greater stemwood biomass yields over the period for all situations other than with the 30-year rotations where no difference occurred, and with case 2 for the 60-year rotations, where yields were actually less than whole-tree harvesting.

Losses of forest floor biomass and N content (fig. 8) increase as rotation length decreases, level of utilization increases and as the intensity of management increases from case 1 to case 2. However, as the intensity of management increases from case 2 to case 3, through fertilization, these losses decrease with net gains being found for stems-only harvesting on 90- and 60-year rotations.

FORCYTE can also be used to examine the economic and energy benefit-cost implications of these management strategies. The results for energy are shown in figure 9. For all management scenarios, the energy benefit/cost ratio over the 180-year period is considerably greater than 1, but it is greatest with the second level intensity of management (thinning) and least with the third level (thinning + fertilization). Trends with rotation length varied depending on the intensity of management. The energy benefit/cost ratio increased with decreasing rotation length for the lowest two levels of intensity of management, but decreased slightly in the case of the third level.

The conclusion reached from these simulations is that yield can be increased by switching from a 90-year rotation with no management to a shorter rotation with increased management and more intensive utilization, but that there is some point before whole-tree harvest with intensive management on a 30-year rotation beyond which increasing demands on the forest may reduce its yield. The intensity level of management and utilization at which this occurs will differ on sites of different quality in different regions and with different species, but could easily be determined by iterative simulations using FORCYTE. FORCYTE can thus be used to determine: (1) combinations of management strategies that will optimize sustained biomass production for specific site conditions; and (2) the strategies that give the best economic return and the highest energy benefit:cost ratios.

It must be pointed out that the predictions in figures 7 to 9 are still qualitative only. They are produced by an unvalidated and as yet incomplete model. They are merely presented to show the potential of FORCYTE. We do feel that they are qualitatively acceptable, however, and work is underway with FORCYTE-11 to compare predictions from the improved, calibrated model with empirical field data.

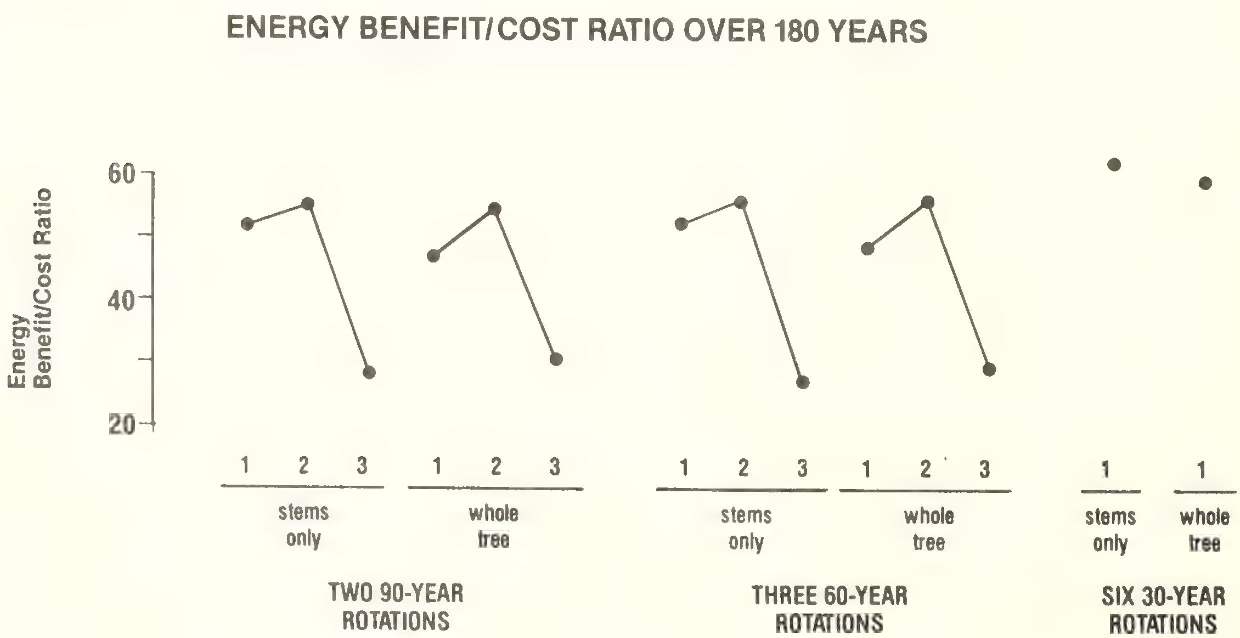


Figure 9.--Summary of the simulated energy benefit:cost ratios for the management and harvesting regimes described in figure 7.

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The FORCYTE model is under the control of the Canadian Forestry Service. Inquiries as to its availability and use should be directed to Dr. Lake Chatarpaul, Project Leader, Petawawa National Forestry Institute, Canadian Forestry Service, Chalk River, Ontario K0J 1J0, Canada, or to J. P. Kimmins, Faculty of Forestry, University of British Columbia, Vancouver, British Columbia, Canada.

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PREDICTING LONG-TERM EFFECTS OF SILVICULTURAL PRACTICES ON FOREST SITE PRODUCTIVITY

Phillip Sollins, Joseph E. Means, and Russell Ballard

ABSTRACT: We describe a system for predicting long-term consequences of silvicultural practices, especially those that may decrease long-term forest productivity. The system requires: (1) conceptual models that incorporate current understanding of interactions among ecosystem processes; (2) process studies that, guided by the conceptual models, allow us to establish equations for the transfer of material and energy among ecosystem components and to refine the conceptual models; (3) a management-oriented simulation model, developed from the conceptual model, used to predict long-term consequences of silvicultural practices; and (4) validation studies that test those predictions. Conceptual models must account for interactions among processes as well as for all material flow. Process studies should clarify the relations between processes and their controlling factors; operational trials should duplicate silvicultural practices to determine their effectiveness. In general, process studies should be replicated at each site, operational trials across many sites. Experimental treatments selected for process studies need not adhere to standard silvicultural practice. Development of a management-oriented simulation model must be a high priority. FORCYTE, developed by J. P. Kimmins and K. A. Scoullar, may offer the best starting point for foresters and researchers in the Pacific Northwest. Operational trials should validate the simulation model rather than merely provide information for specific sites, species, and treatments.

INTRODUCTION

Our understanding of how forest ecosystems function has increased greatly in the last 15 years. Nonetheless, although new silvicultural practices have been proposed and implemented, our ability to predict the long-term effects of these practices has increased little.

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For example, there is increasing concern that more complete removal of forest biomass during harvest will lead to long-term declines in productivity (Boyle 1976, Boyle et al. 1973, Harvey et al. 1980, Kimmins 1977, Leaf 1979). A decline in second-rotation yield has been demonstrated at sites that were windrowed (Ballard 1978) and slash-burned (Keeves 1966), but such long-term studies are few. An even greater problem is that conceptual models are not adequate for addressing the problem (Morrison and Foster 1979, Stone 1979, Tamm 1979).

We urgently need an efficient way to use existing knowledge of forest ecosystems to predict the long-term impacts of silvicultural practices. For

example, the National Forest Management Act requires that the National Forests be managed without "impairment of the productivity of the land" (U.S. Government 1982). Obviously, decisions must be made today based on existing knowledge, and new studies must be initiated as well.

In this paper we describe a system which can help us synthesize information, coordinate research, and utilize existing data to make long-term projections. This system requires four components: conceptual models, process studies, simulation, and validation studies. We define and provide examples of each of these, and show how they can function together as a coordinated system.

CONCEPTUAL MODEL

A conceptual model helps us integrate our understanding of how the forest ecosystem functions. It identifies the important compartments of an ecosystem, the processes by which material and energy are transferred among them, and the relationships among these processes. For example, a conceptual model of forest growth must include the effects of nutrient availability and plant competition (e.g., Linder 1981) as well as the relations between organic matter in the soil and the ability of the soil to supply nutrients to plants (e.g., McGill et al. 1981).

Separate conceptual models may be needed for different subsystems within an ecosystem, such as the forest floor or the tree canopy. But it may be difficult to integrate information about the subsystems without a conceptual model of the entire ecosystem that explicitly shows how such submodels interact.

Conceptual models are often presented as box and arrow diagrams illustrating the transfer of material between compartments (fig. 1). In such material-flow models, an arrow or similar symbol denotes a process and the boxes represent pools of material. These diagrams can easily be converted into quantitative budgets showing the amounts of material transferred along each pathway and changes in pool sizes over a convenient time period such as 1 year (Bormann et al. 1977, Cole et al. 1967, Sollins et al. 1980).

Because the budget accounts for all material flowing through the forest ecosystem, inconsistencies in the data can often be discovered by checking for conservation of mass (Sollins 1982). Ranking the transfers according to the amount of material flowing each year provides an initial estimate of the importance of each process within the ecosystem. Although quantity does not necessarily equate with importance, this procedure offers a useful starting point.

A disadvantage of conceptual models based on material flow is that they cannot easily be used to illustrate interactions among processes.

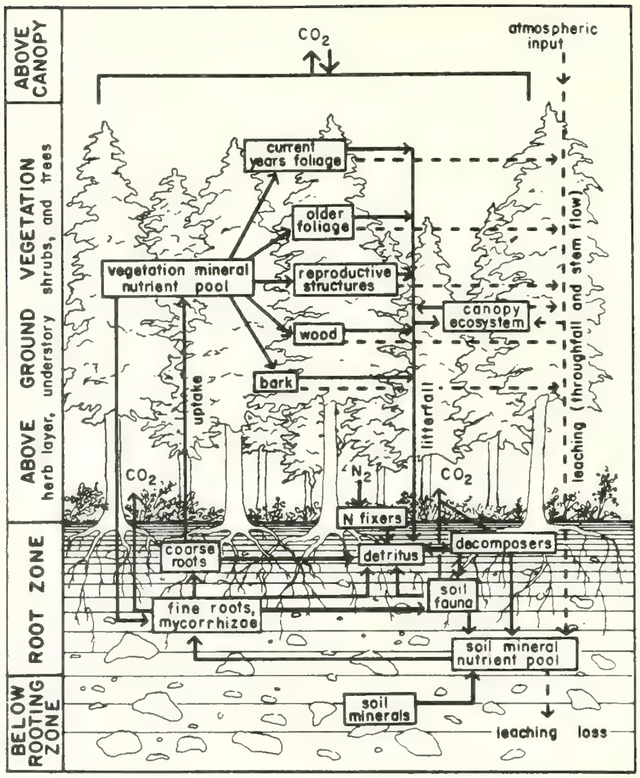

Figure 1.--A conceptual model of material transfer in a coniferous forest (from Johnson et al. 1982).

Although Forrester (1961) proposed a schematic notation for superimposing interactions upon a material-flow diagram, our experience has been that such notation inevitably creates an unintelligible diagram.

Interactions among processes, however, can be represented clearly with diagrams that emphasize the processes rather than the compartments (fig. 2). Word models, written descriptions of interactions among processes (table 1), are also effective. In either, the interactions among processes must be described explicitly. Material-flow diagrams and budgets alone cannot tell the whole story.

Descriptions of interactions, however, can be quite misleading unless they are based on and developed in conjunction with a material-flow budget. Without a material-flow budget, it is too easy to omit an important interaction or process by assuming that we know what is important. Omissions and erroneous assumptions can be corrected, of course, but the trial-and-error approach may prove expensive. First constructing a material-flow budget that accounts for all flow may save considerable effort in the long run.

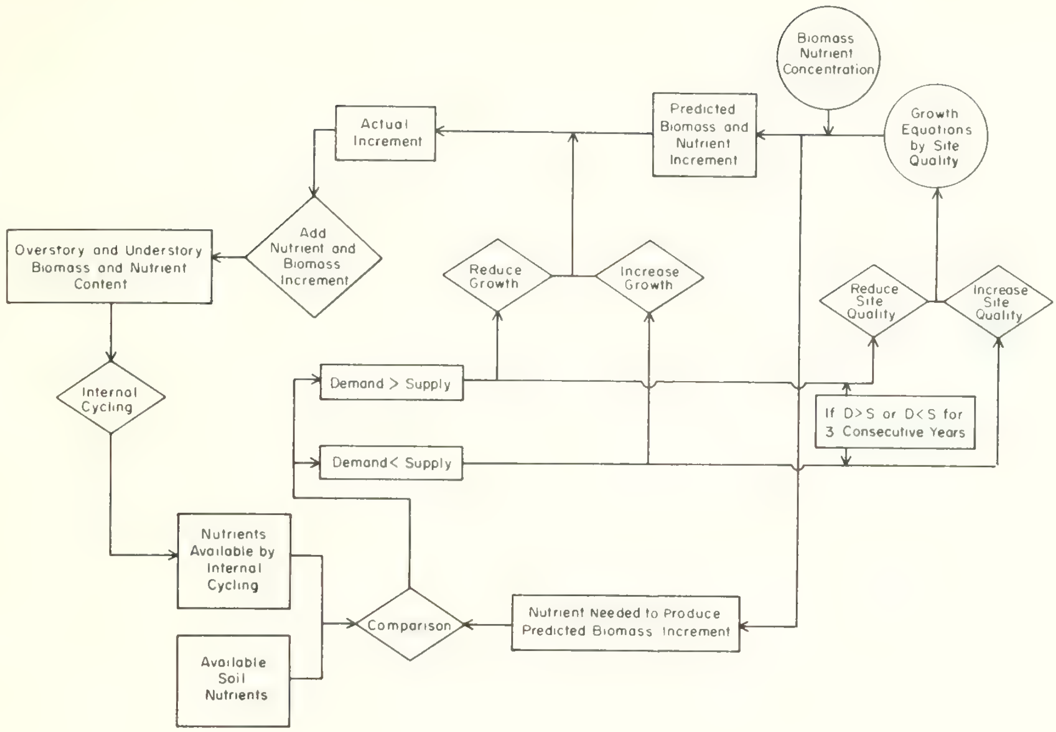

Figure 2.--Diagram showing interactions between nutrient availability and biomass in FORCYTE (from Kimmins and Scoullar 1979).

Table 1--Interactions among modules of CONIFER (from Sollins et al. 1979)

Effect of carbon variables on water and energy flows

A. Foliage biomass affects:
   1. Transpiration
   2. Fraction of rain incident to canopy that strikes foliage, and therefore also fraction striking nonfoliage. (This and following two affect drip, litter, and soil moisture dynamics. There are also indirect effects through percent cover.)
   3. Water retention capacity of canopy
   4. Distribution of retention capacity between foliage and nonfoliage
   5. Fraction of rainfall passing directly to forest floor (through percent cover)
   6. Net longwave radiation input to canopy (through percent cover, which affects input and loss)
B. Stem biomass affects:
   1. Percent cover (and therefore numbers 2-6 above)
C. Fine leaf and woody litter mass affects:
   1. Water retention capacity of litter

Effect of energy variables on carbon and water flows

A. Heat input to canopy affects:
   1. Potential evaporation from canopy
   2. Transpiration
B. Litter temperature affects:
   1. Litter decomposition processes
   2. Potential evaporation from litter
C. Soil temperature affects:
   1. Large and fine root respiration and growth
D. Net heat input to snowpack and heat deficit of snowpack affect:
   1. Net transfer between free water and ice in snowpack

Effect of water variables on carbon and energy flows

A. Soil moisture affects:
   1. New and old foliage photosynthesis (via stomatal resistance)
   2. Fine root death (via plant moisture stress)
   3. Dead root + soil organic matter decomposition processes
B. Litter moisture affects:
   1. Litter decomposition processes
C. Snowpack ice affects:
   1. Litter temperature
D. Snowfall affects:
   1. Heat loss from snowpack due to snowfall
   2. Albedo of snowpack
E. Drip plus direct rainfall affect:
   1. Litter and soil temperature

Table 2--Experimental treatments suitable for process studies

Treatment	Examples of processes affected directly
Trenching (root exclusion)	Uptake, decomposition, respiration
Fertilization	Leaching, decomposition, uptake, nitrification, denitrification
Defoliation	Transpiration, litterfall, light and water interception, photosynthesis
Acidification	Cation exchange, weathering, Fe and Al eluviation
Soil compaction	Water infiltration, soil aeration, surface erosion
Thinning	Photosynthesis, respiration, light and water interception
Devegetation	All heat and water transfers, uptake, decomposition, etc.

PROCESS STUDIES

Process studies, the second component of a systematic approach, attempt to define the relations between each process within the conceptual model and the factors regulating each process. Examples of ecosystem processes include decomposition of foliage litter, N fixation, and photosynthesis. If a conceptual model is built around transfers and accumulation of material and energy, the processes are simply all the flows of material and energy among compartments. Jorgenson et al. (1975) review many of the material-flow processes important in forest ecosystems; Gorham et al. (1979) and McColl and Grigal (1979) describe others.

We have said that process studies attempt to clarify the relations between processes and controlling factors. It is important to separate them from operational trials, which attempt to duplicate a silvicultural management practice to determine its effectiveness. The two have different objectives and therefore different design criteria. An experimental treatment intended to be part of a process study must be designed for easy interpretation of results (table 2). If, for example, litter is to be raked off a plot, then the same amount of litter should be removed everywhere from each plot. To assure uniform treatment, such an experiment is usually conducted by researchers or under their direct supervision. In an operational trial, as in actual management, the amount of vegetation removed, clipped, or sprayed varies greatly within each treatment area. For process studies, however, the treatment needs to be more carefully controlled.

Because most management treatments affect many components of the forest ecosystem simultaneously, such treatments are of limited value in process studies. For example, any site-preparation treatment or harvest method affects the litter layer, the soil, and the vegetation. While it may be easy to identify components that are affected by a management practice, it can be almost impossible to separate cause and effect.

For process studies, then, it is preferable to devise a treatment that affects only one component of a system. Then, when an effect is detected, its cause will be clear. We do not mean, however, to downplay the importance of operational trials. They are critical to the overall research/management process and will be discussed later.

An important feature of any process study is replication. This procedure, however, must be tailored to the researcher's objectives. For instance, by repeating an experiment at many sites, mean and variance can be estimated across a broad range of sites. Such replication, however, gives no estimate of mean or variance at each site, a constraint that may severely limit our ability to extract information about processes. The problem here is that many relations between processes and their controlling factors are nonlinear; for example, a two-fold change in temperature will usually not cause a two-fold change in decomposition rate. Thus, when we try to relate average values for decomposition rates over broad regions to average temperatures over broad regions, we find poor correlations. A single equation can describe the relation (Bunnell et al. 1977a, 1977b), but only if we have a good estimate of the mean temperature and decomposition rate at each site. To obtain site-specific data, measurements and treatments must be replicated at each site. To obtain information applicable to a broad region, studies must be replicated across a wide range of sites. As a rule of thumb, process studies require site-specific information; operational trials require replication across a broad range of sites.

Replication, however, must be approached cautiously. Given deadlines and finite budgets, it will never be possible to measure all processes with the degree of statistical elegance that we might like. To obtain accurate data for one process and ignore other processes entirely may not help, particularly if the process closely studied turns out to be insignificant. An alternative is to first obtain at least some information about all major processes at a site, even if this precludes adequate replication. In poorly defined systems, such as are dealt with in forestry, some initial study of all the processes may be essential. This done, rigorous investigations can begin on those processes that seem to be most important.

In the system we describe here, the object of process studies is to define the factors regulating each process at each site, not to test management strategies. Research objectives should therefore dictate the choice of sites. Experimental forests and Research Natural Areas, such as those operated by the USDA Forest Service and many universities, offer advantages for process research. When research is concentrated at a specific site, the information from one study can be used directly in another without having to account for differences between sites. Baseline meteorological and hydrological data are also frequently available for such sites, increasing the efficiency of process research.

Treatments selected for process studies need not follow standard silvicultural practice or be economically feasible. An excellent example of this is an experiment by Turner (1977) in Douglas-fir stands in western Washington in which N availability was decreased temporarily by adding carbohydrate (sugar) to the forest floor, an expensive and operationally impractical treatment. The C:N ratio of the forest floor was increased markedly, affecting decomposition, leaching of N from the forest floor, and internal redistribution of N within the trees. Occasionally, treatments that adhere to standard practice will prove valuable as part of a process study. If results are monitored for a sufficient time, the treatment can then serve as both an operational trial and a process study.

Simulation models can be important tools for process research. A research-oriented simulation model can be constructed for a selected process or set of processes such as decomposition (Bunnell et al. 1977a, 1977b) or water and energy exchange in forest canopies (Halldin 1979). The output can be compared to the results of process studies in order to verify our understanding of that portion of the system. A sensitivity analysis can be performed on such a model, a procedure in which each parameter value is varied by a fixed percentage in order to see which parameter values influence the process most. Such factors are then obvious candidates for further study.

MANAGEMENT-ORIENTED SIMULATION MODELS

The third component of a systematic approach to predicting forest productivity is simulation. A "management-oriented simulation model," as defined here, is one designed specifically for land managers interested in the long-term effects of silvicultural practices. To be useful, a management model must predict ecosystem behavior over a wide range of environments and time intervals. The model should predict yield, and costs and benefits in terms of both dollars and energy. The model must simulate processes if it is to be extrapolated to combinations of site, species, and treatment outside the experience of its authors. Effects of nutrition must be included. Input requirements and run cost must be kept modest and output format must be convenient or the model will not be used.

A management-oriented simulation model can be developed from the conceptual model once process studies have provided the necessary equations describing each process. Without an adequate conceptual model, progress may be painfully slow and expensive.

Computer simulation is the only way land managers can foresee the behavior of forest ecosystems over many rotations, an interval longer than our life spans. Although projects should be initiated that will span several rotations, we cannot afford to wait for the results. Occasionally, we may find chronosequences of stands that allow us to gather data simultaneously on different stages of natural stand development, but it is difficult to determine how similar the stands were when established (Stone 1975). Moreover, intensive management has only been practiced for a few decades in most forest regions, and few, if any, sites have been managed intensively for several rotations. Thus, although simulation results may be tentative, there are few alternatives.

A good management model allows land managers to select silvicultural alternatives on the basis of the long-term consequences. Most importantly, a good model can help us deal with the problem that each component of the ecosystem is connected to every other--that one cannot be altered without affecting all. For example, fertilization affects many processes simultaneously. In addition to speeding tree growth, it can promote nutrient immobilization by the soil microbiota, increase the rate of litter decomposition, burn roots, and inhibit mycorrhizal development. All of these processes will interact to affect uptake by the trees and their subsequent growth. An adequate description of the effect of fertilizer on tree growth therefore requires a model of the entire system. A computer simulation model can be a practical way to organize such a description, which then becomes a hypothesis for the behavior of the whole system and can be tested by comparing the predicted and observed responses.

A realistic management-oriented simulation model will help research managers to assign research priorities. Through sensitivity analysis, critical processes can be identified and research dollars invested where the need and payoff is likely to be greatest. A model is not a substitute for creative thinking; but to the extent that it reflects our current understanding of the system, it will be a powerful tool for guiding research.

We know of only two management-oriented simulation models for forests that include the effects of nutrient availability. FORTNITE is described by the authors (Aber et al. 1982) as a generalized computer model for organic matter and N dynamics in forest ecosystems. Developed by merging a model of forest floor decomposition (Aber et al. 1978, 1979; Aber and Melillo 1982) and a model of forest succession (Botkin et al. 1972), it treats a 10- x 10-m plot and follows individual trees and age classes of litter through time. Because some processes are assumed to be random, the computer program reports averages over replicate plots. The model has been "parameterized" for a New England hardwood forest and used to predict effects of rotation length, harvest intensity, and fertilization on fiber yield (Aber et al. 1982).

The authors show that it accurately predicts trends in basal area, forest floor biomass, and dead wood mass after clearcutting, although data available for comparison are limited. Using the model, they concluded that extremely short rotations would reduce yield by as much as two thirds, but that fertilization might offset some of the decrease. Whole-tree harvesting on a 90-year rotation yielded more fiber than conventional clearcutting, while selective cutting yielded slightly less.

Hemstrom and Adams (1982) have adapted JABOWA, the forest succession model used in FORTNITE, for use with conifer forests in the Pacific Northwest but have not incorporated the nutrient cycling portion of FORTNITE into their model (V. Dale, personal communication 1983).

The other management-oriented simulation model which includes effects of nutrient availability is FORCYTE (Kimmins and Scoullar 1979). It is designed to predict, on a site-specific basis, the long-term effects that various intensive forest management and harvesting practices may have on nutrient budgets and productivity as well as on energy and economic costs. It uses an input data file to provide the necessary site- and species-specific information and to specify the regeneration, spacing, thinning, fertilization, and harvesting options for each rotation. Many basic ecosystem processes are included in the model (fig. 2). Tree growth is predicted from information on yield in managed and unmanaged stands (see, for example, Hann and Riitters 1982). It is assumed that tree growth will decrease from these measured rates if levels of available N are not sufficient to meet growth demands. The effects of moisture availability are included implicitly by recognizing three site classes labeled good, medium, and poor. A site can change from one site quality class to another in response to proper (or improper) management. Early versions of this model were designed for even-aged, single-species forests managed on rotations of less than 150 years; but the model can be adapted to other stand structures and forest types. As of 1983, FORCYTE had been used for 4 years as a teaching tool at the University of British Columbia and at Oregon State University. It was also being modified for use with western hemlock in the Oregon Coast Range, subtropical *Eucalyptus* plantations in Brazil, black spruce in Alaska, radiata pine in South Australia, and several other forest types.

Both FORTNITE and FORCYTE incorporate most of the information on nutrition and productivity available in the regions for which they were designed. Both models, however, have limitations. Neither has yet been validated adequately against independent data. But with refinement and more validation, both could become valuable management tools in their respective regions.

VALIDATION STUDIES

Under validation, the fourth component needed to predict long-term productivity, we include any procedure by which we increase our confidence in the correctness of a model. This depends on the similarities between observed and predicted responses, the number of model variables checked, the treatments involved, and the length of time, range of sites and climatic conditions over which comparisons are made. Validation studies must eventually span two or three rotations if long-term predictions of the model are to be verified.

To be meaningful, validation studies must compare model predictions with experimental data that were not used to construct the model. Once the current version of the model has been validated, the results of the study can be used to construct a refined version. A new, independent set of data is then needed to validate this refined model.

Operational trials can play a critical role in the validation process. Such trials allow us to test many parts of the model at once because they affect various ecosystem processes simultaneously. Note that this is precisely the reason why we suggested that most operational trials are not suited for process studies.

Extensive operational trials, conducted by industry and agencies, already cover a wide range of sites and treatments (table 3). Because the data have already been collected, such studies can be used to validate the model at an extremely low cost. All too often, the data from operational trials are used only to provide information on the effects of a particular silvicultural practice at a particular site or set of sites. Their value increases if they are used to validate a model that can then be extrapolated to other sites and silvicultural treatments and through time.

Many studies not generally considered operational trials may also serve to validate management-oriented models. Several long-term studies of effects of insects, animal activity, and disease on growth and yield (table 3) could be particularly valuable because they include processes and interactions seldom addressed in silvicultural trials. For example, if disease or severe damage by insects or other animals is noted during a fertilizer trial, measurements are sometimes discontinued on the affected plots. Such action may be understandable because the object of the study was to gauge fertilizer response. But insects and disease are important components of the forest ecosystem and have considerable impact on yield; including such interactions in a model and validating it accordingly will increase its usefulness as a management tool.

Operational trials, too, will be more useful for model validation if key ecosystem processes and pools are monitored, not just the amount of biomass removed. The measured processes should be those that sensitivity analyses have shown will have a critical effect on the accuracy of the predictions.

Such monitoring can provide two important benefits. First, weak parts of the conceptual model can be identified and then improved with process studies. Second, the process data can provide an additional check on the validity of the underlying conceptual model. For example, it is conceivable that a management model could predict yield

Table 3--Operational trials and other experiments suitable for validating models of long-term productivity

Treatment	Example	Reference[1/]
Fertilization	Northwest Regional Forest Fertilization Project	(1)
Levels of utilization (harvesting intensity)	Department of Energy study at Pack Forest and elsewhere	(2)
Multiple rotations	Long-term CFI plots in southern Australia already spanning several rotations	(3)
Thinning	Levels of Growing Stock Study in Pacific Northwest	(4)
Sludge application	University of Washington/Metro Study	(5)
Vegetation control	CRAFTS Project	(6)
Mixed species plantings	Alder/Douglas-fir mixes at Wind River and Cascade Head; Oregon State University LTER study on Douglas-fir/Ceanothus mixes	(7)
Insect control	Effects of levels of tussock moth defoliation on Douglas-fir growth	(8)
Animal damage	Animal damage impacts on conifer plantations	(9)
Disease	Levels of *Dothistroma pini* control	(10)
Irrigation	SWECON (in combination with fertilization and insect control)	(11)
Site/residue treatment	Pacific Northwest residue treatment studies	(12)
Fire	Prescribed burning in southeastern U.S.A.	(13)
Soil removal	Soil removal during site preparation	(14)
Drainage	Drainage intensity, southeastern U.S.A., coastal plain	(15)

[1/] (1) Peterson and Gessel 1983
(2) Cole and Bigger 1983
(3) Keeves 1966
(4) Williamson 1976
(5) Edmonds and Cole 1980
(6) Preest 1975
(7) Miller and Murray 1978
(8) Wickman 1963
(9) Black et al. 1979
(10) Gilmour and Noorderhaven 1971
(11) Aronsson and Tamm 1982
(12) Cramer 1974
(13) Stone 1971
(14) Glass 1976
(15) Terry and Hughes 1978

correctly on occasion yet still be substantially incorrect in its representation of internal processes. A model that accurately predicts rates of such processes *and* crop yield is much more likely to be correct in a wide range of circumstances.

Long-term growth and yield plots deserve special mention. The Pacific Northwest has an unusually large number of these with records spanning up to 48 years and areas as large as 42 ha (Sollins 1982, Williamson 1976). Additional plots have been established by the USDA Forest Service that, if maintained over the next few decades, will provide comparable information (Hawk et al. 1978). These plots offer our only opportunity to check model predictions over long periods of time through the use of records of tree growth and mortality. They also give us the only opportunity to conduct process research at sites for which such records are available. Consequently, these plots must be protected. Buffers must be maintained because clearcutting to the edge of the plots will inevitably increase mortality within them. Salvage operations within the plots also must be prevented if forest floor and soil processes are to be studied.

INTEGRATING THE FOUR COMPONENTS

The overall object of the system described here is to increase our understanding of forest ecosystems (the conceptual model) and our ability to predict the long-term consequences of silvicultural practices (the management model). We illustrate this with a diagram containing two feedback loops (fig. 3).

The left-hand loop through the conceptual model and process studies is the primary way to improve the conceptual model. The loop begins when available knowledge is synthesized into an initial

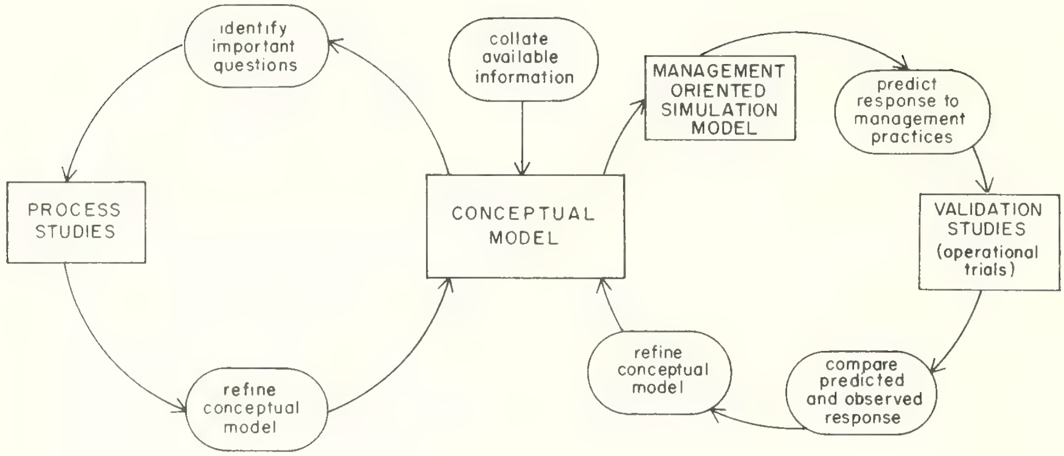

Figure 3.--Feedback loops between research and management operations.

conceptual model describing ecosystem structure and function. The conceptual model helps determine the priorities for process studies. In turn, the results of the process studies serve to refine the conceptual model.

The right-hand loop through the conceptual model, the management model, and the operational trials (fig. 3) enables us to make increasingly reliable predictions for forest management. Once constructed, the management-oriented simulation model can be updated to incorporate refinements in the conceptual model that have resulted from process studies. Furthermore, validation of the management model will improve both it and the conceptual model. Note that discrepancy between predicted and observed responses forces modification of both models; agreement reinforces confidence and discourages change. Neither discrepancy nor agreement is necessarily good or bad. Discrepancy opens up exciting possibilities for research; agreement means that land managers have a useful tool on which to base their decisions.

With diligent and creative effort by researchers and land managers, steady progress is inevitable. But the rate of progress cannot be measured without a clear goal. There is no reason to refine the management model unless it is inadequate for predicting responses within prescribed limits. Selection of such responses and limits is the responsibility of researchers and land managers together.

Efficient progress toward an understanding of the long-term effects of silvicultural practices requires cooperation among forest managers and many research disciplines: silviculture, geology, soils, nutrition, mensuration, microbiology, plant physiology, entomology, pathology, economics, and perhaps others. Information must flow freely across disciplines, as well as between researchers and land managers. Some validation studies must be long-term, perhaps as long as two or three rotations. These require thorough documentation and conscientious protection of study sites. In addition, existing studies and data sets should be used by many researchers if the studies are to realize their full potential. Cooperative studies are essential for all these reasons.

Existing cooperative research projects can help with the coordination of new studies. Such projects include the Regional Forest Nutrition Research Project (Peterson and Gessel 1983), the CRAFTS (Coordinated Research on Alternative Forestry Treatments and Systems for Forest Vegetation Management) program (Walstad et al. 1982) and the North Carolina State Forest Fertilization Cooperative in the southeastern United States (Allen and Duzan 1983), as well as the entire IUFRO program. With modest funding, such cooperatives can help (1) coordinate research to avoid duplication, (2) coordinate large-scale testing of models already under development, and (3) provide forums where researchers and land managers can discuss results and needs. Assignment of research priorities and standardization of methods are other possibilities, but we must keep in mind that the objective is to promote progress, not stifle creative thinking. In general, our goal is to use data efficiently to solve land-management problems. If we can assure that this will happen, we have a logical basis for seeking expanded funding for research into the long-term behavior of forest ecosystems.

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POTENTIAL IMPACTS OF SOME HARVESTING OPTIONS ON NUTRIENT BUDGETS OF A GMELINA PULPWOOD PLANTATION ECOSYSTEM IN NIGERIA

L Chelunor Nwoboshi

ABSTRACT: The N, P, Ca, and Mg budgets of a 10-year-old Gmelina pulpwood plantation ecosystem in southern Nigeria were estimated. With the data, the likely impacts of removing these elements using three harvesting methods (thinning, coppice-with-stand, and clearfelling) coupled with three utilization levels (stemwood only, bole only, and bole plus branches) on future productivity of the site were assessed.

Thinning up to 50 percent of the smaller stems coupled with complete utilization of the aboveground biomass did not seriously deplete nutrient reserves. Increasing the harvesting intensity, beyond thinning, combined with any level of utilization increased nutrient drain with the greatest loss occurring under clearfelling combined with the removal of boles and branches.

Rates of depletion differed for specific nutrients. Phosphorus depletion was most rapid followed by those of Ca, N, and Mg. With use of either coppice-with-stand or clearfelling, P and Ca are likely to limit productivity in the second and third rotations, respectively. The potentials and limitations of using this approach to forecast limiting nutrients and when they would occur in managed forest ecosystems are discussed.

INTRODUCTION

Plantations of *Gmelina arborea* L. are being established in Nigeria to supply cellulose for the manufacture of paper and paper products. To maximize the productivity of fiber the adoption of an intensive harvesting method that would enable the recovery of as much pulpable material as possible is being contemplated. The methods being considered include: *thinning* in which the standing stock could be reduced by fellina 25 to 50 percent of the smallest diameter class trees, coppice-with-stand in which only 25 percent of

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the biggest diameter class trees are retained; and clearfelling involving the removal of all the trees at the rotation age of 7 to 10 years. All residual trees are to be managed on a 40-year rotation.

These methods are to be combined with either the removal of stemwood only, bole (stemwood and stembark) only, or bole plus branches and in each case leaving the remaining aboveground biomass as slash. Lack of knowledge of the long-term effects of any of these intensive harvesting techniques on future site productivity makes the choice of the best technique for any given site difficult.

In the past two decades, researchers working in temperate forest ecosystems (Bednall 1968, Boyle and Ek 1972;, Boyle et al. 1972, Keeves 1966, Weetman and Webber 1972, White 1974) have indicated that the increased removal of biomass and its nutrient content by intensive harvesting can cause a decline in future productivity of forest sites. Their reports also showed that the impact of such harvests may vary with the site and the species. There is need to know the probable rates at which such nutrient depletions could occur under various forest management practices, whether or not the drain of all nutrients would occur at the same rate, and if not, the order in which they would become growth-limiting under a given management regime. To adopt an efficient management system that could delay fertilizer application, or enable the forester to anticipate the order in which the nutrients will become limiting, answers to the above questions are needed.

The object of this study was to evaluate the potential impacts of using the various harvesting and utilization options mentioned above on the N, P, Ca, and Mg status of a Gmelina pulpwood plantation ecosystem.

MATERIALS AND METHODS

Study Area.

The study was carried out in Gambari Forest Reserve (Longitude 3°52'E. Latitude 7°10'N., 120m elevation) situated about 20 km south of Ibadan, Nigeria. The area has a mean annual rainfall of about 1 600 mm and mean maximum and minimum temperatures of 25°C and 21°C, respectively. The soil is brown to reddish sandy loam with granite schists and gneiss as parent materials (Anon. 1957). The soil is also generally well drained and slightly acidic in reaction.

Prior to the establishment of the plantations, the site carried a mixed, tropical, semi-deciduous forest according to Keay's (1959) classification. The plantations were established by taungya system using Gmelina stumps raised under similar conditions at the Gambari forest nursery and a planting spacing of 2.4 m by 2.4 m. No thinning has been done on the plots sampled in this study.

Sampling Procedure.

Two sample plots (0.05ha) were located in a 10-year-old stand and diameter at breast height (d.b.h.) of all the enclosed trees were measured and classified into four d.b.h. classes, using one-quarter of the diameter range as the class interval. Two trees from each diameter class whose d.b.h. were nearest the mean d.b.h. of the class were harvested as the class sample trees. Eight trees representing diameter sizes in the stand were used in the study.

Each sample tree was felled near the groundline; and the total height, bole length (measured to the first major living branch), diameter overbark (d.o.b.) and diameter underbark (d.u.b.) at both ends of the stem are measured. All leaves, branches, and small boles were weighed in the field and representative samples taken for dry weight determinations. For large boles, fresh weight of stemwood and stembark were derived from their volume calculated with the Smalian formula (Spurr and Barnes 1954) and the average of their densities determined on three discs, one each from the middle and both ends of the bole.

The undergrowth and litter in two random 2.5 m x 2.5 m quadrants within each plot were gathered and sorted into litter, foliage (including climbers and small branches), and woody stems. These were (fresh) weighed in the field and subsamples were oven-dried at 70°C for dry weight determination.

Three composite soil samples, each taken from 20 auger points, were collected to a depth of 30 cm to estimate the macronutrient (N, P, Ca, and Mg) content of the soil zone containing the bulk of the feeding roots. These were air-dried and sieved to pass a 2 mm sieve.

All the plant and soil samples were analysed for their N, P, Ca, and Mg concentrations. Total N concentrations in both plant and soil samples were determined by the Semimicro Kjeldahl method (Mackenzie and Wallace 1954). Plant P, Ca, and Mg were estimated from plant solutions prepared by wet-digestion using a ternary acid mixture of nitric, sulphuric, and perchloric (5:1:1) acids. Phosphorus was then determined according to Barton (1948) and Ca and Mg by atomic absorption spectrophotometry in a 1-percent lanthanum chloride solution. Available P in soil was determined using Bray and Kurtz method no. 1 (1945), and exchangeable Ca and Mg were determined, as for the plants, from normal ammonium acetate extracts.

RESULTS AND DISCUSSION

Biomass and Its Distribution.

The total stand biomass per hectare at the end of the first 10-year rotation and the distribution are shown according to size class and tree com-

Table 1 - Biomass distribution among d.b.h. classes in a 10-year-old stand (in kg/ha)

Plants Components	D.B.H. SIZE CLASSES (cm) A (12.75-20.25)	B (20.26-27.75)	C (27.76-35.25)	D 35.26-42.75)	TOTAL
Tree no./ha	285	191	252	318	1,046
Leaves	409.75	659.40	782.65	5,645.89	7,497.69
Branches	6,928.79	7,191.94	10,109.71	22,579.59	46,810.03
Stembark	560.56	294.35	6,457.00	8,618.08	15,929.99
Stemwood	13,501.92	7,756.33	82,530.91	97,740.59	201,529.75
Total Shoot	21,401.02	15,902.02	99,880.27	134,584.15	271,767.46

ponent in table 1. The stemwood consistently dominated the biomass in each of the site clases, and the foliage formed the smallest component. Similary, the D size class, which formed the dominant members of the canopy, contained the highest total biomass followed by the C class of the codominant trees. These two size classes (C and D) had over 87 percent of the total aboveground stand biomass. The suppressed members (A and B classes) made up less than 13 percent.

Ca, Mg, N, and P Uptake and Distribution.

The percentage concentration and contents of Ca, Mg, N, and P in the various size classes and tree components at age 10 are shown in table 2. The concentration of each element varied with the tree components and inconsistently with the diameter size classes. The leaves had the highest and the stemwood the lowest concentrations of N, P, and Mg in all size classes. Calcium concentration was highest in the stembark followed by either the leaves or the bolewood.

Variation in concentration notwithstanding, the content of each element tended to follow the biomass trend. For instance, the stemwood with relatively low concentrations of these elements held the highest quantity of each element owing to the greater biomass.

The C and D classes which had the bulk of the biomass similarly held the bulk of the nutrients. At 10 years, the stand carried a total of 2 425 kg Ca, 960 kg N, 615 kg Mg, and 371 kg P. Of these, 76 to 90 percent, depending on the element, were held in the stemwood and 80 to 93 percent in the C and D diameter size classes.

The Ecosystem Nutrient Budgets.

The quantities of total N, available P, and exchangeable Ca and Mg in the soil to a depth of 30 cm as well as the quantities of these elements in the aboveground biomass, undergrowth, and litter on the forest floor are shown in table 3. Available data on other sources of nutrient losses and additions have also been included.

The total ecosystem nutrient content varied with the element and ranged from Ca (6 015 kg/ha) through N (2 784 kg/ha) and Mg (2 149 kg/ha) to P (428 kg/ha). Their distribution among the ecosystem components also varied with the elements.

Table 2 - N, P, Ca, and Mg content and distribution in a 10-year-old Gmelina plantation

Nutrients	Plant Components	D.B.H. CLASSES (cm) A (12.75-20.25)		B (20.26-27.75)		C (27.76-35.25)		D (35.26-42.75)		Total
		(%)	(kg)	(%)	(kg)	(%)	(kg)	(%)	(kg)	(kg)
N	Leaves	0.49	1.97	0.63	4.15	0.64	5.00	0.40	22.36	33.48
	Branches	0.24	16.63	0.43	30.86	0.54	54.51	0.31	70.34	172.34
	Stembark	1.35	9.18	4.91	18.10	0.42	33.32	0.40	41.76	102.37
	Stemwood	0.42	56.92	0.65	50.26	0.26	216.69	0.25	327.58	651.44
	Total		84.70		103.37		309.52		462.04	959.63
P	Leaves	0.16	0.66	0.14	0.92	0.18	1.41	0.24	13.55	16.34
	Branches	0.24	16.63	0.14	10.07	0.14	14.15	0.14	31.61	72.46
	Stembark	0.18	1.22	0.56	2.00	0.16	12.52	0.06	6.12	21.93
	Stemwood	0.06	7.75	0.28	21.69	0.12	98.86	0.10	132.26	260.39
	Total		26.26		34.68		126.94		183.24	371.12
Ca	Leaves	1.25	5.12	1.50	9.89	1.77	13.84	0.60	33.87	62.72
	Branches	0.47	32.74	0.28	20.14	0.51	51.56	0.37	83.34	187.78
	Stembark	2.41	16.37	2.75	18.70	1.23	96.36	0.87	91.17	222.60
	Stemwood	0.80	107.83	0.80	61.94	0.88	729.13	0.80	1052.58	1951.48
	Total		162.06		110.67		890.89		1260.96	2424.58
Mg	Leaves	0.20	0.82	0.37	2.42	1.08	8.44	0.28	15.81	25.49
	Branches	0.05	3.15	0.12	8.38	0.13	12.94	0.16	34.13	60.85
	Stembark	0.24	1.63	0.90	3.22	0.14	11.32	0.09	9.28	25.44
	Stemwood	0.10	13.48	0.10	7.98	0.27	218.59	0.20	263.15	502.96
	Total		19.08		22.00		251.29		322.37	614.74

Table 3 - N, P, Ca, and Mg budgets in a 10-year-old Gmelina pulpwood plantation ecosystem (kg/ha)

Ecosystem components	Biomass	Nutrients (kg/ha) N		P		Ca		Mg	
	(mt/ha)	(%)	(kg/ha)	(%)	(kg/ha)	(%)	(kg/ha)	(%)	(kg/ha)
Trees									
Leaves	7.50		33.48		16.34		62.72		25.49
Branches	46.81		172.34		72.46		187.78		60.85
Stembark	15.93		102.37		21.93		222.60		25.44
Stemwood	201.53		651.44		260.31		1951.48		502.96
Total	271.77	34.5	959.63	86.7	371.12	40.31	2424.58	28.6	614.74
Undergrowth									
Leaves) Branches) Climbers)	9.52		52.36		1.33		39.98		13.33
Woody Stem	0.84		2.44		0.12		1.68		0.84
Total	10.36	2.0	54.80	0.33	1.45	0.69	41.66	0.66	14.17
Litter	6.72	1.0	30.24	0.28	1.21	0.80	48.38	0.50	10.75
Influx									
Rainfall[1]		0.5	15.0	0.12	0.5	0.17	10.19	0.10	2.12
Biological Fixation		?	?						
Soil Reserve[2]		62.0	1724.8	12.55	53.7	58.03	3490.5	70.1	1507.50
Total Ecosystem		100	2784.47	100	427.98	100	6015.31	100	2149.28
Losses									
Erosion			3.4		13.1		203.1		18.1
Run-off[3]			9.6		2.9		29.0		7.3
Total Known Loss			13.0		16.0		232.1		25.4

1 Blay 1980
2 Lal 1978
3 To 30-cm depth

For P with low availability in the soil, about 87 percent of the total ecosystem stock was held in the vegetation and 12.5 percent in the soil. On the other hand 29 percent Mg, 39.5 percent N, and 40 percent Ca were held in the vegetation while 70, 62, and 58 percent of Mg, N, and Ca, respectively, were held in the soil. For each of the elements, therefore, the standing crop and the soil formed the major nutrient pools. The undergrowth and the litter components held only a small fraction of the nutrient stock.

Impact of Various Harvesting Options.

Productivity of forest ecosystems is sustained largely by the circulation of mineral nutrient elements. According to Jorgensen et al. (1975) the key to an adequate supply of nutrients on most forest sites is the nutrient cycle which allows reuse of essential plant nutrient elements. Consequently, any alteration of the forest ecosystem that directly or indirectly results in substantial loss of nutrients participating in the nutrient cycle will lead to loss of productivity on sites where such nutrients are in limited supply.

Many investigators (Boyle and Ek 1972, Jorgensen et al. 1975, Kimmins 1977, Tamm 1969, Weetman and Webber 1972, Will 1968) who have assessed the effects of intensive forest management practices on site productivity have done so largely by determining the magnitude of the losses and evaluating their significance in relation to the total nutrient economy of the ecosystem. That approach was adopted in this study for the assessment of the significance of losses of N, P, Ca, and Mg through thinning, coppice-with-standard, or clearfelling coupled with either the removal of stemwood, stemwood plus its bark, or bole plus branches.

The quantity of biomass and N, P, Ca, and Mg removed by the above harvesting options are shown in tables 4 and 5. Thinning or cutting away 25 percent of the lowest diameter trees removed 162 kg Ca, 85 kg N, 26 kg P, and 19 kg Mg from the vegetation nutrient pool or 3, 3, 6, and 1 percent, respectively, of their total content in the ecosystem. Increasing the thinning intensity to involve the removal of up to 50 percent of the lowest diameter trees increased the biomass harvest by 74 percent and the quantity of N and P removed by over 200 percent. This heavy thinning intensity, however, removed only 14 percent of the biomass and 4, 7, 14, and 2 percent of the total ecosystem Ca, N, P, and Mg, respectively, indicating that thinning has limited effects on the ecosystem nutrient stock.

Using the coppice-with-stand technique, 50 percent of the crop biomass and 44, 19, 18 and 14 percent of the total ecosystem P, Ca, N, and Mg, percent of the total ecosystem P, Ca, N, and Mg, respectively, were removed from circulation. In clearfelling, all the crop component of the ecosystem is removed at one time. This causes an abrupt interruption of the cycle of all the nutrients in the ecosystem.

The quantities of these elements eventually removed from circulation in the ecosystem varied, however, with the amount of the biomass carried away from the site. Under any of the above har-

Table 4 - Potential biomass removal (kg/ha) under various harvesting options

Utilization levels	Harvesting options: Thinning 25% (A class)	50% (A + B classes)	Coppice-with-stand	Clear-felling
Stemwood only	13 501.92	21 258.25	103 789.16	201 529.75
Bole only	14 062.48	22 113.16	111 101.07	217 459.74
Bole + Branches	20 991.27	36 233.89	135 331.51	264 269.77
Total Shoot	21 401.02	37 303.04	137 183.31	271 767.46

Table 5 - Potential N, P, Ca, and Mg removals under various harvesting options and their possibleimpacts on future site productivity

Utilization options	Thinning 25% (A) Qty. per rotation (kg)	No. of 10-Yr. rotations	Thinning 50% (A + B) Qty. per rotation (kg)	No. of 10-Yr. rotations	Coppice-with-stand (A + B + C) Qty. per rotation (kg)	No. of 10-Yr. rotations	Clearfelling (A + B + C + D) Qty. per rotation (kg)	No. of 10-Yr. rotations
			Nitrogen					
Stemwood only	56.92	48.92	107.18	25.98	323.87	8.60	651.45	4.27
*Bole only	66.10	42.13	134.46	20.71	384.47	7.24	753.81	3.69
Bole plus branches	82.73	33.66	181.95	15.30	486.47	5.72	926.15	3.00
Total Shoot	84.70	32.87	188.07	14.81	497.59	5.60	959.63	2.90
			Phosphorus					
Stemwood only	7.75	55.22	29.44	14.54	128.30	3.34	260.56	1.64
Bole only	8.97	47.71	32.66	13.10	144.04	2.97	282.42	1.52
Bole plus branches	25.60	16.72	59.36	7.21	184.89	2.31	354.98	1.21
Total Shoot	26.26	16.30	60.94	7.02	187.88	2.28	371.52	1.15
			Calcium					
Stemwood only	107.83	55.79	169.77	35.43	898.90	6.69	1951.48	3.08
Bole only	124.20	48.43	204.84	29.37	1030.33	5.84	2174.08	2.77
Bole plus branches	156.94	38.33	257.72	23.34	1134.77	5.30	2361.86	2.54
Total Shoot	162.06	37.12	272.73	22.06	1163.62	5.17	2424.58	2.48
			Magnesium					
Stemwood only	13.48	159.44	21.46	100.15	240.05	8.95	503.20	4.27
Bole only	15.11	142.22	26.31	81.69	256.22	8.39	528.65	4.07
Bole plus branches	18.26	117.70	37.84	56.80	280.68	7.06	587.25	3.66
Total Shoot	19.08	112.65	41.08	52.32	292.37	7.35	614.74	3.50

*Bole = Stemwood + Stembark.

vesting methods, the greater the biomass removed, the higher the quantity of nutrients removed from the site.

If we assume that similar quantities of each element are held in each tree component at the end of each subsequent 10-year rotation, the ability of the ecosystem to sustain future productivity under the above harvesting and utilization options can be calculated in terms of number of potential rotations. Such calculations (table 5) indicate that the higher the harvesting intensity and the utilization levels, the greater the impact or lower the number of rotations of sustained productivity. For each element, the most severe impact was caused by clearfelling coupled with the removal of all the shoot components from the site, and the least impact was when low thinning of 25 percent of the stock was combined with the removal of only the stemwood. In addition to greater nutrient depletion through biomass removal, several workers have indicated that clearfelling also induces other forms of nutrient losses. Bunn and Will (1973), Lal (1978), McColl and Grigal (1979), and Stone (1973) have shown that clearfelling induces accelerated leaching of soluble salts, accelerated decomposition of organic matter, and accentuates nutrient losses through erosion and run-off. According to Lal (1978), losses of N, P, Ca, and Mg through the combined actions of erosion and run-off around the study area could amount to 13, 16, 25 and 232 kg/ha, respectively. Such losses are likely to be sustained in the study site during the first year after the clearfelling operation. Adding these losses to those sustained under the various utilization levels will further reduce the period of sustained productivity.

The rate of nutrient drain varied, however, with the elements. Under heavy thinning or greater harvesting intensities, and at all utilization levels, phosphorus loss was most rapid. This is apparently due to the lower content of its available form in the ecosystem and the immobilization of about 90 percent of this in the tree crop. Using the heavy thinning, the next limiting nutrients were N followed by Ca and Mg, whereas if the coppice-with-standard technique or the clearfelling system is adopted to harvest Gmelina on a site with similar or lower N, P, Ca, or Mg status as this study site, P fertilization may be

needed during the second rotation followed by Ca, N, and Mg fertilization on the third rotation.

These forecasts are valid, however, only if the soil-extraction procedures measure the amount of soil nutrient that become available to the plants over the forecasted rotations and the rooting system is restricted to the surface 0-30 cm of the soil. Very little is known about the N-fixation and chemical weathering rates in these soils, and in practice some roots do penetrate beyond the 30-cm depth. This indicates that mineral weathering, biological N-fixation, and deeper rooting could provide additional sources of N, P, Ca, and Mg for the trees and could prolong the period of sustained productivity without fertilization. If the ratio of the newly acquired nutrients remained the same, however, the trends of the impacts of the various harvesting and utilization levels on the site nutrient "budget" and the order in which the nutrients will limit growth are likely to remain unaltered. It is therefore evident that adoption of either the coppice-with-standard or the clearfelling system will quickly deplete the P status and more slowly the status of N, Ca, and Mg in the ecosystem and that the removal of additional biomass to the conventional bole will further accelerate the rate of nutrient depletion. (Since,) In the absence of physical damage to the soil, nutrient drain can be replaced by fertilization, and the choice of a more intensive harvesting or utilization option rests on whether or not the value of the additional biomass will compensate for the additional cost of fertilization. In the tropics where forest fertilization has not become a routine silvicultural tool, adoption of heavy thinning and utilization levels that leave tree components with high nutrient content as slash on the forest floor are advocated.

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IMPACT OF SHIFTING CULTIVATION ON THE SOIL OF THE TROPICAL RAIN FOREST IN THE BENAKAT DISTRICT, SOUTH SUMATERA, INDONESIA

Kazuto Arimitsu

ABSTRACT: Alang-alang grasslands are widespread in the South Sumatera Province of Indonesia as a result of shifting cultivation. The impact of shifting cultivation has changed the natural tropical rain forests to various stages of secondary forests and grasslands. The latosolic and red-yellow podzolic soils under these various vegetational covers have little diversity in their chemical properties, strong acidity, and relatively low levels of organic carbon, nitrogen, and exchangeable cations. Their physical properties vary with the differences in vegetational cover. The soils under natural forests have fairly good water permeability, greater total porosity, and large pores. The soils under grasslands or Pinus merkusii plantations have lower water permeability, somewhat higher bulk density, and lower porosity.

INTRODUCTION

Broad grasslands occur in the Benakat District of South Sumatera, Indonesia. Although they look like savanna, they belong to the tropical rain forest zone. It is considered that the repeated cutting and burning by shifting cultivation and pasturage have caused the extermination of the natural and secondary forests allowing various types of grasslands. Several attempts at reforestation and afforestation have been made in this district for soil and water conservation and for maintaining wood resources. Most have failed because of the inadequate natural and socio-economical conditions.

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This paper examines the differences in soil properties brought about by the different vegetation types resulting from different regimes of clearing and burning.

Study Area.

The study area is in the Benakat District of South Sumatera Province, latitude 3°20' -4°25' S. and longitude 103°07' -104°14' E., from about 10 to 120 m above sea level, and about 180 km south-west of Palembang (fig. 1). The climate is tropical, and wet, without pronounced dry months. At Muaraenim, 40 km south of the study area, annual precipitation is 3 020 mm and mean annual temperature is 26.5° C (mean from 1965 to 1974). All months receive more than 100 mm of rain. The terrain is mostly undulating to rolling as a result of the dissection of the peneplain of the Musi River basin by numerous small tributaries.

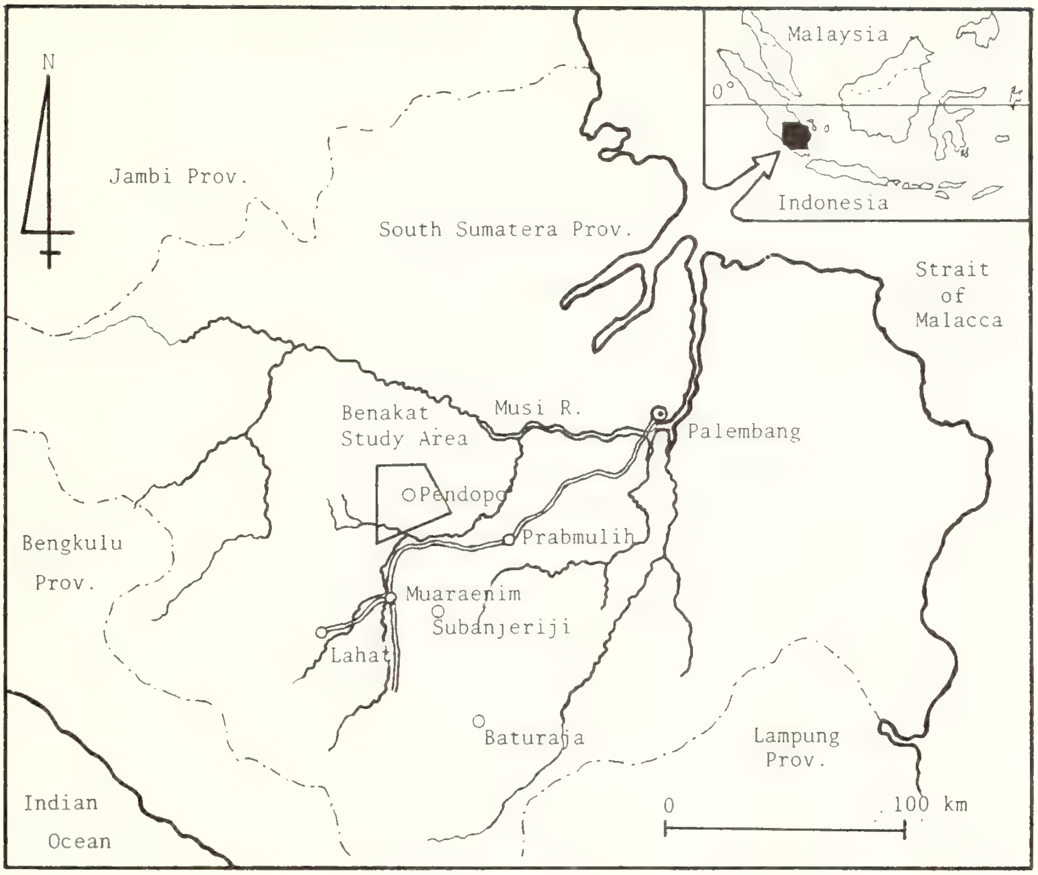

Figure 1. Location of the study area.

The study area mainly consists of tertiary formations of the upper and lower Palembang beds. The Palembang beds consist principally of mudstones derived from acid volcanic materials. Although a natural tropical rain forest with Lauraceae and Dipterocarpaceae exists near Rambutan Village, most of the vegetation cover in the study area is grassland with a scattering of poor secondary forest in some parts. Small clumps of pine that have survived the wild fires are the result of afforestation attempts in the area.

METHODS

The impacts of the disturbance of vegetation caused by shifting cultivation or pasturage on the soil properties were evaluated on five plots of different vegetation types: (1) alang-alang (*Imperata cylindrica*) type grassland, (2) *Melastoma affine*-alang-alang type grassland, (3) 13-year-old *Pinus merkusii* plantation on a grassland, (4) secondary forest, and (5) natural forest. All five of these plots were located in similar topographical positions on the upper plateau of the study area.

The morphological features of the soils on the five plots were surveyed and the physicochemical properties of soil samples were analyzed. Soil pH was measured on both 1:2.5 soil-water and soil-1N KCl extract using a glass-electrode pH meter. Total carbon and total nitrogen were measured by the dry-combustion method using a CN Corder (Yanaco MT 500W). Exchangeable cations were extracted with a 1N solution of ammonium acetate (pH 7) and were determined by atomic absorption. Cation-exchange capacity was also measured with a 1N ammonium acetate solution with the procedure of NH_4 saturation and distillation of NH_3 from sodium chloride extract. Physical properties were determined from samples taken at the site with 100-cm^2 x 4-cm cores. Pore-space distribution and water permeability were determined by Mashimo's method (Mashimo 1960) using the core samples.

RESULTS AND DISCUSSION

Soil Morphology.

The soils of the five plots under different vegetational cover show only slight morphological variation (table 1) except for P.16 soil which has a sandy texture derived from a different parent material. All the soils have rather thin A horizons, but the secondary and natural-forest soils have slightly thicker A horizons than the other soils. All soils show an increase of clay content with depth and have argillic horizons.

Table 1--Morphology of five soils in the study area

Soil	Vegetation	Horizon	Depth (cm)	Color, moist (mottle)	Texture[1/]	Structure[2/]	Other Remarks
P.1	Melastoma affine-alang-alang grass-land	Ao(L)	0.5-0				
		A1g	0-10	10YR4/3(10YR4/2,4/6)	SiC	bk	
		B21tg	10-20	10YR5/4(7.5YR5/6)	C	bk	
		B22tg	20-40	10YR6/4(7.5YR5/8)	C	bk	
		B3cn	40-60	2.5Y6/4(7.5YR5/8)	HC		Iron nodules
		BC1g	60-90	2.5Y6/4(2.5YR5/8)	HC		Plinthite
		BC2gcn	90-94	2.5Y6/4(2.5YR4/6)	HC		Iron nodules
		BC3g	94-100+	2.5Y7/3(2.5YR5/8)	HC		Plinthite
P.5	Alang-alang grassland	Ao(L)	0.5-0				
		A1g	0-10	10YR4/3(10YR4/2,5/6)	SiL	sbk	
		B21tg	10-26	7.5YR5.5/8(2.5Y5/6)	SiL	bk	
		B22tg	26-40	7.5YR5/8(2.5Y5/6)	SiC	bk	
		B23tg	40-62	7.5YR5/8(2.5Y5/6)	C		Iron nodules
		B3cn	62-70	7.5YR5/8	C		Plinthite
		BC1g	70-85	5YR5/8(2.5Y6/6)	C		Plinthite
		BC2g	85-100+	2.5YR4.5/8(2.5Y6/6)	C		Plinthite
P.7	Pine plantation	Ao(L)	0.5-0				
		A1g	0-10	10YR4/4(2.5Y5/4)	SiL	bk	
		B21tg	10-30	7.5YR4.5/6(2.5Y5/4)	SiC	bk	
		B22tg	30-65	7.5YR5/6(2.5Y5.5/4)	C	abk, sbk	
		BCg	65-100+	7.5YR5/6(2.5Y6/4)	C		Plinthite
P.15	Natural forest	Ao(L)	1-0				
		A1g	0-15	5YR5/8(10YR6/4)	SiL	sbk	Fissures
		B21tg	15-35	5YR5/8(2.5Y6/2)	SiC	sbk	Fissures
		B22tg	35-46	2.5YR5/8(2.5Y6/4)	C		
		B23tg	46-80	2.5YR4/8(2.5Y7/4)	C		
		B24tg	80-100+	2.5YR4/8(2.5Y7/4)	C		
P.16	Secondary forest	Ao(L)	1-0				
		A1	0-20	10YR3/3	SL	cr, bk	
		B1g	20-40	10YR4/3(2.5Y5/4)	SL	bk	
		B2tg	40-85	2.5Y6/6(2.5Y5/4)	SC		
		C	85-100+	10YR6/8			

[1/]SiC: Silty clay, C: Clay, HC: Heavy clay, SiL: Silt loam, SL: Sandy loam, SC: Sandy clay.

[2/] bk: Blocky, sbk: Subangular blocky, abk: Angular blocky, cr: Crumb.

They are thought to be red-yellow podzolic soils accompanying some latosolic features. They also have grayish- or reddish-colored patterns, or a pronounced mottled pattern. The soils are classified as belonging in the Aquults suborder of the United States Soil Taxonomy (Soil Survey Staff 1975). The C horizons of the soils with red and white mosaic mottles are considered to be plinthites. The soils with the plinthites (P.1, P.5, and P.7) are classified as Oxic Plinthaquults. The soils with horizons of hard iron-nodules (P.1 and P.5) cannot be differentiated at the subgroup level of Plinthaquults because the distinction of the subgroups of Plinthaquults is incomplete and provisional in the United States Soil Taxonomy (Soil Survey Staff 1975). The soils without pronounced plinthite are classified as Typic Paleaquults (P.15) and Aeric Paleaquults (P.16).

Soils in the study area are morphologically similar to some of the Baturaja-Martapura soils in *Imperata* grassland 100 km southeast of the study area which were reported as being Tropoudults or Paleudults by the Soil Research Institute, Indonesia (1975). Red-yellow podzolic soils with soft or hard plinthite also were reported by Mohr and others (1972). Soils with hard iron nodules and soft plinthite in the study area may be related to the Oxic Plinthaquults of Mohr and others (1972), but detailed chemical and mineralogical analyses are needed for more precise classifications.

Tanimoto (1981) studied the floristic composition and succession of the vegetation in the study area and made a scheme of plant succession. According to his study, the alang-alang type grassland is the result of frequent burning and

Table 2--Chemical properties of five soils in the study area

Soil	Horizon	pH H_2O	pH KCl	Organic C	Total N	C:N ratio	$CEC^{1/}$	Exchangeable cations Ca	Exchangeable cations Mg	Exchangeable cations K
				(%)	(%)		(me/100 g)			
P.1	A1g	4.8	3.7	2.65	0.21	13	12.70	2.96	1.18	0.16
	B21tg	5.0	3.7	1.52	0.14	11	11.68	2.26	0.85	0.03
	B22tg	5.1	3.7	1.12	0.11	10	11.82	1.49	0.56	0.05
	B3cn	5.0	3.7	0.82	0.08		11.91	0.32	0.13	0.13
	BC1g	5.0	3.6	0.58	0.06		16.22	0.30	0.13	0.13
	BC2gcn	5.1	3.6	0.25	0.03		14.74	0.06	0.08	0.14
P.5	A1g	4.8	3.7	2.45	0.24	10	8.97	0.99	0.40	0.14
	B21tg	4.7	3.7	0.95	0.12	8	7.51	0.33	0.05	0.06
	B22tg	4.8	3.7	0.76	0.10	8	7.96	0.29	0.04	0.09
	B23tg	4.8	3.8	0.65	0.10	7	8.11	0.12	0.03	0.06
	B3cn	4.9	3.9	0.68	0.08		9.84	0.08	0.03	0.07
	BC1g	4.8	3.7	0.49	0.09		10.09	0.07	0.04	0.07
	BC2g	4.8	3.7	0.43	0.06		11.75	0.05	0.04	0.10
P.7	A1g	5.0	3.8	1.66	0.16	10	12.22	2.12	0.86	0.07
	B21tg	4.7	3.7	0.87	0.13	7	11.31	0.15	0.16	0.08
	B22tg	4.7	3.6	0.67	0.09		12.54	0.10	0.19	0.08
	BCg	4.7	3.6	0.56	0.10		14.75	0.11	0.21	0.10
P.15	A1g	4.3	3.6	1.92	0.17	11	10.75	0.08	0.15	0.09
	B21tg	4.4	3.7	1.10	0.11	10	10.06	0.10	0.11	0.06
	B22tg	4.4	3.6	0.97	0.09		10.35	0.04	0.06	0.05
	B23tg	4.5	3.7	0.76	0.09		10.83	0.03	0.04	0.05
	B24tg	4.7	3.7	0.65	0.06		14.63	0.13	0.02	0.07
P.16	A1	4.5	3.8	1.96	0.18	11	5.43	0.10	0.08	0.06
	B1g	4.8	4.1	0.76	0.06		2.45	0.03	0.02	0.02
	B2tg	4.8	4.1	0.57	0.07		2.78	0.02	0.01	0.01
	C	4.8	4.0	0.33	0.04		2.15	0.02	0.01	0.02

1/CEC: Cation-exchange capacity.

will not return to tree communities, whereas the Melastoma affine-alang-alang type grassland appears with infrequent burning and will change to secondary forest. Soils under both types of grasslands and pine plantations have no significant differences in their morphological features. Even the soils under the natural and secondary forests have profiles rather similar to those of the grassland soils, but they have slightly thicker A horizons and stronger structure or fissure development with deeper root penetration.

Chemical Properties.

The five soils have slight variations in their chemical properties (table 2). All the soils have strong acidity throughout their horizons and have fairly low content of carbon, nitrogen, and exchangeable cations. All soils have low cation-exchange capacities. Soils under the natural and secondary forests have somewhat less carbon, nitrogen, and exchangeable cations in their surface horizons than do the soils of the grasslands and the pine plantation. Although Sanchez (1976) concluded that organic carbon and total nitrogen in the tropical soils were basically no different from that of the temperate regions, the soils in this study area apparently have lower levels of carbon and nitrogen. The tropical forest can grow at the soils of very low fertility because the soil and forest have a remarkably closed nutrient cycle (Sanchez 1976) and most nutrients are stored and utilized in the biomass. Organic matter and nitrogen increase slightly after burning but decrease gradually with cultivation. The magnitude of this decrease is greater in cases where the soil surface is exposed for considerable periods of time (Sanchez 1976). The grasslands in the study area have been subjected to shifting cultivation and abandonment for some time, and their fertility has been lowered to the present level.

Physical Properties.

The five soils have rather great variations in their physical properties (table 3). The soils under grasslands tend to have greater bulk den-

Table 3--Physical properties of five soils in the study area

Soil	Horizon	Bulk density	Water permeability[1/]	Pore space[2/] Total	Large
		(g/cm^3)	(cc/min)	- - - % - - -	
P.1	A1g	1.13	13	56.7	14.6
	B21tg	1.32	8	50.8	11.7
	B22tg	1.36	0.3	52.7	15.1
	B3cn	1.55	15	53.0	11.4
	BC1g	1.32	4	55.8	12.9
P.5	A1g	1.27	10	49.6	17.7
	B21tg	1.37	4	53.5	17.4
	B22tg	1.38	8	50.3	18.6
P.7	A1g	1.29	18	52.0	19.1
	B21tg	1.30	3	54.9	19.0
	B22tg	1.45	0.5	47.7	10.6
	BCg	1.43	2	48.6	7.6
P.15	A1g	1.03	160	63.7	29.6
	B21tg	1.12	85	59.6	18.5
	B22tg	1.18	32	58.0	12.1
	B23tg	1.17	9	60.2	11.6
P.16	A1	1.04	89	58.9	29.6
	B1g	1.13	43	58.3	43.4
	B2tg	1.19	112	56.6	37.9

[1/] Saturated hydraulic conductivity measured with a 100-cm^2 x 4-cm core and a 2-cm water head.

[2/] Large pore space is equivalent to pF 2.7 tension.

sity, lower water permeability, lower porosity, and lower amounts of large pores than the soils of the natural and secondary forests. The soils of the alang-alang grassland and the Melastoma affine-alang-alang grassland have no significant differences in their physical properties, but soil under the pine plantation on a grassland displays some differences. Differences may be attributed to the deterioration of the soil structure which is reflected in the morphological features of the soil profiles. Changes in nutrient budgets and soil microclimate brought on by changes in vegetation change the physical properties of the soil. Sanchez (1976) suggested that significant changes in soil physical properties took place when the nutrient cycle was broken by clearing and burning.

CONCLUSION

Significant changes in soil physical properties take place when a natural tropical rain forest is converted to an alang-alang grassland by shifting cultivation or pasturage, while morphological and chemical properties of the soil change very little. The differences in soil physical properties under various vegetation types should be taken into account when afforestation or reforestation sites are selected in the humid tropics.

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JARI: A LESSON IN TROPICAL FORESTRY

C. E. Russell, C. F. Jordan and R. M. North

ABSTRACT: Jari Florestal e Agropecuaria in the eastern Amazon is the world's largest tree farm with well documented sites at various stages of conversion from native forest to second-rotation pulpwood plantations. The standing stock of four nutrient elements in the native forest is being compared with those present in plantation forests of various ages. The entrance and exit of these elements was monitored by quarterly collections of rain from five weather stations and soil water from 37 zero-tension lysimeters.

The calcium element stock present in the phytomass and soil, the calcium cycle, and the wood production of a native Amazon forest is compared to a Pinus caribaea plantation on the sandy soil (Alfisols) at Jari Florestal. Conversion from native forest to pine plantation increased the wood production/hectare twofold. There was a concomitant loss of approximately 576 kg Ca/ha or about 45.3 percent of the standing stock of the calcium inventoried in the native forest. Thus, we speculate on the basis of calcium alone, that the productivity of second and subsequent rotations will be much lower than the first rotation unless fertilization is practiced.

INTRODUCTION

The Amazon forest is one of the oldest and largest forests in the world. Geologically, the Amazon Basin is enclosed by the Andes to the west, the ancient Guiana shield to the north, and the Brazilian shield on the south, all consisting predominantly of granitic and metamorphic rock. This topography has forced the weathering products of these enclosing structures to settle into a relatively closed basin. These sediments have been exposed to lengthy and various cycles of weathering, erosion, and sedimentation, constantly recycling and leaching the nutrients they originally contained (Fittkau et al. 1975).

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Since the time of Alexander von Humboldt, it has been firmly believed that the luxuriant forest of the Amazon Basin was an indicator of very fertile soils and that the region would eventually become a great granary. Soil analyses have shown that these soils are, in fact, among the poorest on earth. Recent studies indicate that the native forest overcomes the nutrient scarcity in the soils by a tight recycling of nutrients (Herrera et al. 1978a, Herrera et al. 1978b, Jordan and Herrera 1981, Klinge and Fittkau 1972, Stark and Jordan 1981). Some ecologists now believe that these soils are not important sources of nutrients, and that once the recycling mechanisms of the native forest are disrupted, nutrient elements will be rapidly leached from the system. If this is true, sustained yields are not possible in the Amazon Basin. Harcombe (1977a, 1977b) has challenged this idea and, on the basis of several experimental plots in Costa Rica, has concluded that nutrient leaching is not great enough to affect the productive potential even after clearing the site. While there exists considerable controversy pertaining to the productivity of tropical forests, there are limited data to support the various hypotheses. Part of the problem results from the assumption that all tropical forests have similar structure and function.

The sites of the studies reported in this paper are the plantations of Jari Florestal e Agropecuaria in the eastern Amazon Basin. Jari is a Brazilian company, formerly owned by a United States shipping firm. The plantations consist of approximately 1.6 million ha on both sides of the Rio Jari, the last major tributary on the north side of the Rio Amazonas. The annual rainfall is about 2 300 mm. Elevations range from 5 to 500 m. Soils vary tremendously from deep organic to sand dune alluvium and deep kaolinite clays. This study was confined to the sandy soils (Alfisols) only. Extreme annual temperatures vary from 18^{o} to 35^{o}C. There is a wide variation in rainfall: The wettest months are April-May and the driest are October-November (fig. 1 and 2).

This study reports the measurement of calcium element stock in the soil and phytomass, the calcium cycle, and the wood production of a native Amazon forest in comparison to the productivity, calcium stock, and cycle in a first-rotation Pinus caribaea plantation at Jari Florestal, Para, Brazil.

METHODS

To determine the change in the standing stock of nutrient elements with conversion, we measured the phytomass and nutrient content in a native forest and compared it to that of a 9.5-year-old Pinus caribaea plantation. Both sites were on the same soil type, an Alfisol.

The physical dimensions and structure of the native forest were ascertained by means of 66 points in a modified point quarter study (Cottam and Curtis 1956, Cottam et al. 1953) supplemented with four destructively sampled 0.01-ha quadrant plots. The phytomass present in pine plantations and recently converted native forest was ascertained by means of three 0.01-ha quadrant plots. All components were measured and weighed

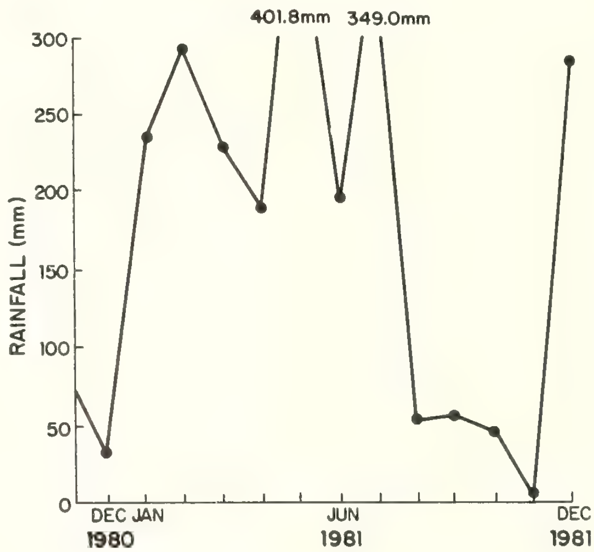

Figure 1.--Monthly precipitation at Mount Dourado, Para, Brazil, December 1980-December 1981.

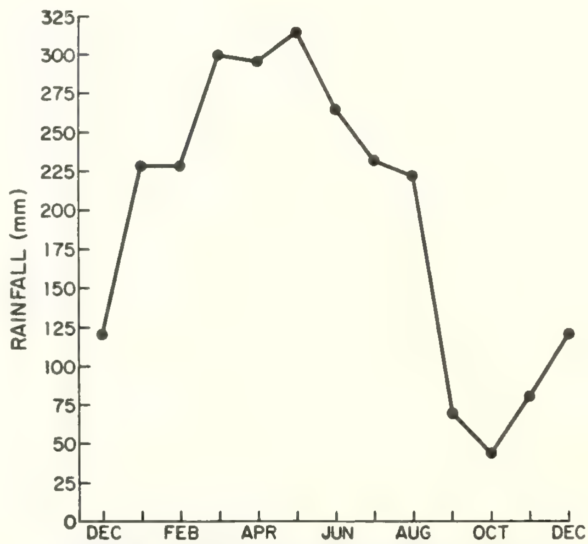

Figure 2.--Average monthly precipitation recorded at Mount Dourado, Para, Brazil, 1968-1981.

Figure 2.--Average monthly precipitation recorded at Mount Dourado, Para. Brazil, 1968-1981.

in the field, then subsamples were taken to the lab to be oven dried at 50°C for 48 hours or until constant weight was obtained. Canopy trees were defined as those plants more than 5 m tall, and understory was defined as those plants between 1 and 5 m in height.

Regression equations were developed from complete harvest of 13 trees in the native forest to estimate phytomass as a function of diameter, height, and wood density (Monk et al. 1969, Whittaker and Marks 1975). These equations did not differ significantly from those of Jordan and Uhl (1978) for native forest in the central Amazon Basin. Diameter increments of 47 individual trees were carefully measured over 1 year by the methods of Jordan and Farnworth (1983). These diameter increments were converted to annual wood production through the use of the regression equations.

To estimate nutrient leaching during the conversion process, we installed soil water collectors (lysimeters) in the following series of plots: (1) native forest, (2) native forest 4 months after logging, (3) native forest 1 month after logging and burning, (4) native forest 13 months after logging, burning, and planting of pine seedlings, and (5) 10-year-old pine plantation. Thirty-seven zero-tension lysimeters (Jordan 1968) were installed in December 1980 to collect soil water at a depth of 30 cm. Water collection began in March 1981 and continued into January 1982.

Jari Florestal maintains five weather stations. The station at Monte Dourado has been collecting precipitation data since 1968. These data were used to calculate a 14-year-average monthly precipitation (fig. 2). Rain water for chemical analysis was collected over a 13-month period from mid-December 1980 to mid-January 1982. Rain was collected in polyethylene jars fitted with a funnel containing a glass wool plug to prevent insects and large particles from entering the jars.

Root phytomass and soil bulk densities were determined by digging nine 1-m^3 pits, randomly located, in each of the study sites. Roots from each pit were collected and weighed. Uniform volumes (410 cc) of soil were taken at three depths (surface, 30 cm, and 100 cm) within the pit and weighed after air drying. Surface soil was that collected from 0 to 4.5 cm deep.

Calcium analysis of rain water and soil water was performed on a Perkin-Elmer 303 Atomic Absorption Spectrometer. Plant and soil samples were analyzed using plasma emission spectroscopy on a Jarrell-Ash Plasma Atom Comp. model 750. Soil samples were processed by the double acid extraction procedure, and plant tissues were dry ashed at 500°C (Jones 1977).

We present just the calcium data here because it is the only element for which analysis has been completed. Analysis of data for potassium, magnesium, and phosphorus is in progress.

RESULTS

The calcium concentration varied from about 18 parts per million (ppm) at the surface to 1.6 ppm at 1-m depth in the Alfisol under the root mat of the native forest (table 1). This is increased to about 423 ppm at the surface when the forest is logged, burned, and converted to a *Pinus caribaea* plantation, and declines to about 73 ppm over 9.5 years of plantation (table 1). The bulk density of the surface soils at the native forest and pine plantation sites were about 1.2 g/cc ($\bar{X}_{n=9}$=1.225, S.D. = 0.3158 and 1.232 g/cc, S.D. = 0.2400, respectively). Thus, the total available calcium in the surface soil was approximately 10 kg/ha in the native forest soil and about 40 kg/ha in the pine plantation (tables 2 and 3).

Table 1--Summary of the calcium concentration in sandy soil at three sites representing native forest and conversion to pine plantation at Jari Florestal, Para, Brazil, August 1980.

Sample depth	Native forest $\bar{X}$(n=9)[1/]	Native forest S.D.[2/]	Native forest to pine (6 mo.) $\bar{X}$(n=9)	Native forest to pine (6 mo.) S.D.	Pine (9.5 yr.) $\bar{X}$(n=9)	Pine (9.5 yr.) S.D.
	(ppm)					
Surface (to 4.5 cm)	17.75	22.27	423.35	470.73	73.26	70.24
30 cm deep	1.41	1.65	0.96	1.48	0.82	1.40
1 m deep	1.60	1.50	0.38	0.76	0.64	1.06

1/ Mean value for n observations

2/ Standard deviation of mean

Table 2--The phytomass (dry weight), average percentage of calcium and calcium content of native forest and sandy soil at Jari Florestal, Para, Brazil (1980)

Component	Phytomass and soil	Ca	Ca
	(t/ha)	(% Dry wt.)	(Kg/ha)
Root mat	12.485	0.91	113.61
Downed wood	6.175	0.15	9.26
Litter-detritus	5.663	0.32	18.12
Undergrowth	20.104	0.32	64.02
Trees: wood	311.238	0.18	560.23
Trees: bark	43.160	0.62	267.59
Trees: foliage	6.906	0.23	15.88
Roots	81.774	0.26	212.61
Subtotal (Phytomass)	487.505		1261.32
Soil (to 4.5 cm)	551.250	0.0018	9.92
Total Phytomass and Soil	1038.755		1271.24

Table 3--Calcium content of a 9.5-year-old Pinus caribaea plantation on sandy soil at Jari Florestal, Para, Brazil (1980)

Component	Phytomass and soil	Ca content	Ca
	(t/ha)	(% Dry wt)	(kg/ha)
Litter and duff	23.83	0.32	76.26
Downed wood	31.68	0.11	34.85
Undergrowth	2.50	0.43	10.75
Pines: bole	176.24	0.12	211.49
Pines: needles	30.78	0.55	169.29
Pines: branches	25.19	0.19	47.86
Pines: root	54.54	0.15	81.81
Subtotal (phytomass)	344.76		632.31
Soil (to 4.5 cm)	554.40	0.0073	40.47
Total (phytomass and soil)	899.16		672.78

The phytomass (dry weight in t/ha) of the native forest and a 9.5-year-old pine plantation is presented in tables 2 and 3. The dry weight times the average percent calcium gives calcium present in each component. The data presented in tables 2 and 3 indicate that 99.22 percent of the calcium in the native forest resides in the phytomass and 93.98 percent is in the phytomass of the pine plantation.

Comparing the total calcium inventory of native forest (1 271.24 kg/ha) with that of pine plantation (672.78 kg/ha), including 21.81 kg Ca/ha estimated to have been removed during thinning of the pine plantation, approximately 576.65 kg Ca are unaccounted for (table 4).

Table 4--Comparison of calcium content between native forest and 9.5-year-old Pinus caribaea plantation at Jari Florestal, Para, Brazil (1980)

	Phytomass and soil (to 4.5 cm)	Ca content	Ca
	(t/ha)	(% Dry wt)	(kg/ha)
Native forest	1038.76	0.12	1271.24
vs.			
Pine plantation	899.16	0.07	-672.78
Pine thinned (bole)	13.63	0.16	-21.81
Net difference between native forest-pine plantation			576.65

During the study of atmospheric input and exit of nutrient elements by leaching, 2 366.9 mm of rain fell in 1981 (fig. 1). This was slightly higher than the 14-year average at Monte Dourado of 2 291.9 mm rain/year (fig. 2). Analysis of this water for Ca^{++} content is presented in table 5. There was a rain water input of 16.25 $kg.ha.^{-1}13\ mo^{-1}$ or about 15 $kg.ha.^{-1}yr^{-1}$. Since rain water was collected after passing through glass wool this is not the total atmospheric input and thus represents a minimum estimate of calcium input.

Table 5--Summary of rain water analysis for five weather stations at Jari Florestal from mid-December 1980 to mid-January 1982.

	Calcium concentration	Precipitation	Calcium input
	(ppm)	(mm)	(kg/ha)
Dec-Feb 1980-81	$\bar{X}_{n=15} = 1.706$	558.7	9.53
Mar-May 1981	$\bar{X}_{n=20} = 0.295$	820.8	2.42
Jun-Aug 1981	$\bar{X}_{n=25} = 0.280$	595.4	1.67
Sep-Nov 1981	$\bar{X}_{n=7} = 1.543$	109.6	1.69
Dec-Jan 1981-82	$\bar{X}_{n=19} = 0.295$	320.0	0.94
		2404.5	16.25

1/ 282.4 mm recorded for December 1981 and 37.6 collected first week of January 1982.

Using Molion's (1975) estimate that approximately 50 percent of the rainfall in the area of the Jari plantation is returned to the atmosphere through evapotranspiration (E_t) one could estimate that the soil water sampled by the zero-tension lysimeters in the native forest is 1 183.45 mm (table 6). Swank and Douglass (1974) estimate that the E_t of a pine stand, is approximately 20 percent greater than a deciduous forest. Because this pine plantation is in the tropics, we assume that the E_t for the 10-year-old pine stand is approximately equal to the native forest. Thus, we assume that about 1 200 mm of soil water should be passing the lysimeters in the pine plantation (table 6). The remaining three estimates of E_t are based on an interpolation between very little E_t immediately after logging and burning to 50-percent E_t for an undisturbed native forest.

The data presented in table 6 suggest that during the conversion process, which involves logging and burning, the greatest loss of calcium by leaching is in the first few years. By the time the pine plantation is approaching harvest size (i.e., 11-12 years), it is losing calcium at about the same rate as the native forest and approximately equal to the 15 $kg.ha.^{-1}yr^{-1}$ input in rainfall (tables 5 and 6). Interpolation of yearly calcium loss by leaching from the various aged sites indicates a total leaching loss of 200 to 250 kg/ha over the 4- to 5-year period it

able 6--Estimated change in calcium flux during conversion of native forest to pine plantation at Jari lorestal, Para, Brazil (1981).

ite	Calcium conc. in Lysimeter Water	Estimated Evapotranspiration	Volume Soil water Passing Lysimeter[1/]	Calcium Leached
	(ppm)	(%)	(mm)	(Kg.ha.$^{-1}$ yr^{-1})
. Native forest	1.368	50[2/]	1183.45	16.19
. Native forest logged August 1980 (7-17 mo.)	2.452	30	1656.83	40.63
. Native forest logged and burned December 1980 (3-15 mo.)	4.979	15	2011.87	100.17
. Native forest converted to pine December 1979 (15-27 mo.)	4.563	20	1893.52	86.40
. Pine plantation 10.25-11 yrs. old	1.232	50	1183.45	14.58

1/ Based on rainfall of 2 366.9mm for 1981
2/ Molion, L.C.B. 1975

takes the pine canopy to close. Subtracting 225 kg/ha from the 576 kg/ha net difference between native forest and pine plantation leaves approximately 351 kg Ca/ha unaccounted for. This 351 kg Ca/ha is either carried out in smoke and ash during the burn, or is an error in measurement.

CONCLUSION

This study accounts for 72.5 percent of the difference in calcium between the native forest and pine plantation. We have demonstrated that 99.22 percent of the calcium in the native forest is in the phytomass, not in the soil. During the conversion process, 45.3 percent of the calcium present in the native forest is lost. In the 9.5-year-old pine plantation (age when phytomass and soil sampling began), 93.98 percent of the calcium is in the phytomass and 6.02 percent is in the soil. Thus, while the calcium content of the soil was improved and the wood production increased from approximately 12 t/ha in the native forest to 21 t/ha in the pine plantation (table 7), it was at a cost of 576.65 kg Ca/ha or about 45.3 percent of the calcium stock in the native forest.

If only boles are removed in the harvest of this pine plantation, about 250 kg Ca/ha will be taken from the site. This leaves about 423 kg Ca/ha for the second rotation. If leaching during site preparation and canopy closure is only two-thirds of that in the conversion from native forest to pine plantation, there will barely be sufficient calcium in the system to complete a second rotation. We speculate, on the basis of calcium alone, that the productivity of second and subsequent rotations will be much lower than the first rotation unless fertilization is practiced.

Table 7--Standing stock and annual productivity of native forest and Pinus caribaea plantations at Jari Florestal, Para, Brazil (1980-1981)

	Standing phytomass (Dry Wt)	Productivity (Dry Wt)
	(t/ha)	(t.ha^{-1} yr^{-1})
Native forest	487.51	11.99
<u>Pinus caribaea</u> (9.5 to 11 yrs)	344.76	20.92

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SOIL BIOLOGY AND FOREST PRODUCTIVITY: OPPORTUNITIES AND CONSTRAINTS

David A. Perry and Sharon L. Rose

ABSTRACT: Various soil microbes may have a positive influence on tree growth. Effects of mycorrhizae are numerous and well known. Other microorganisms play a role in higher plant defense against pathogens. Site disturbance, such as clearcutting and slash burning, has profound, sometimes persistent, effects on the soil microbial community. Mycorrhizal formation may be decreased in disturbed soils, though this doesn't always happen. Burning results in a dramatic increase in the numbers of bacteria relative to fungi, and also alters species composition within the bacterial community. These changes can result in increased pathogenicity to tree seedlings.

INTRODUCTION

Forest productivity is usually thought of as a physiological response to the physical environment. Productivity is manipulated by genetic selection or by enhancing factors such as nutrients, light, and water. The biological environment enters into this scheme in a relatively narrow sense as pests, pathogens, or competitors.

Energy fixation is ultimately a physiological process; however, it is also an ecological process in the sense that it is influenced by numerous interactions, both positive and negative, among the myriad organisms that comprise the biological component of the ecosystem. Biological interactions within the soil are among the most important, and least understood, determinants of tree growth. Decomposers, nitrogen (N) mineralizing bacteria, symbiotic and free-living N fixers, mycorrhizal fungi, rhizosphere bacteria, fungal pathogens, and nematodes interact within the soil matrix to influence, either directly or indirectly, the growth of higher plants (Coleman et al. 1983). It follows that alteration of the soil community can affect tree growth, and therefore has potential as a silvicultural tool. Unlike our more traditional silvicultural tools, however, alteration of the soil biological community occurs in the managed ecosystem whether we like it or not. Thus this resource may be managed either to produce positive impacts or reduce negative ones. In either case we must understand the way the system works to predict the consequences of our actions.

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ECTOMYCORRHIZAE AND TREE GROWTH

General Characteristics of Ectomycorrhizae

As there are recent, excellent reviews of this subject (e.g., Fogel 1980, Marks and Kozlowski 1973, Marx and Krupa 1978, Trappe and Maser 1977), we shall be very brief. Mycorrhizae (literally "fungus-roots") are symbiotic associations between fungi and plant roots. Ectomycorrhizae, common on gymnosperms and some angiosperms, can generally be distinguished from endomycorrhizae by the presence of a "Hartig net," an intercellular network of fungal hyphae within the root cortex (Marx and

Krupa 1978); and by the presence of an often dense hyphal mantle around feeder roots, although some endomycorrhizae may also form a mantle (Hayman 1978). Ectendomycorrhizae, a third type sharing features of both ectomycorrhizae and endomycorrhizae, are relatively unimportant ecologically (Marx and Krupa 1978).

Thousands of fungal species form ectomycorrhizae, including probably all hypogeous fungi (generally those producing belowground fruiting bodies) and most of those which fruit aboveground (epigeous) in forests (Trappe and Maser 1977). Some ectomycorrhizal fungi are restricted to relatively few host species, for example members of the important genus Rhizopogon form mycorrhizae primarily on pines or on Douglas-fir (Molina and Trappe 1982). Other ectomycorrhizal fungi are cosmopolitan in host perference. Cenococcum geophilum forms ectomycorrhizae with over 200 species of plants, and Pisolithus tinctorius is known to associate with 73 different tree species (Marx and Krupa 1978). As with all organisms, the ability of ectomycorrhizae to successfully occupy a given habitat (i.e., a tree root) may be modified by numerous environmental factors. Mycorrhizal species have been shown to vary in pH requirements (Marx and Krupa 1978), drought tolerance (Mexal and Reid 1973, Parke 1982, Theodorou 1978) and sensitivity to litter leachates (Chou-Chou 1978, Alvarez et al. 1979, Schoeneberger and Perry 1982, Rose et al. in press). Worley and Hacskaylo (1959) and Mutah (1972) (both cited in Marx and Krupa 1978) show that under droughty conditions C. geophilum succeeds other fungi on tree roots. Schoeneberger and Perry (1982) found significant differences between ectomycorrhizal types formed in adjacent soils that had been disturbed to different levels.

Competition between fungal species may play a role in ectomycorrhizal formation. Cenococcum geophilum, though readily forming ectomycorrhizae with Douglas-fir under laboratory conditions (Molina and Trappe 1982), is apparently a minor component of Douglas-fir grown in forest soil (Pilz and Perry in press, Schoenberger and Perry 1982). This may be because C. geophilum competes poorly with species, such as Rhizopogon vinicolor, that aggressively infect Douglas-fir roots. This idea is supported by the fact that western hemlock, not a host for R. vinicolor (Molina and Trappe 1982), forms abundant C. geophilum ectomycorrhizae when grown in the same soil as Douglas-fir (Schoenberger and Perry 1982). Competition between fungal species is apparent in the case of Thelephora terrestris, a common greenhouse contaminant that forms abundant ectomycorrhizae only when other fungal species have been eliminated by steam pasteurization.

Ectomycorrhizae and Tree Growth

Many tree species, perhaps most, cannot survive without proper ectomycorrhizal symbionts. Marx and Krupa (1978) list the following benefits to the host: longevity of feeder roots; increased rate of nutrient absorption; greater selectivity of ion absorption; resistance to root pathogens; and increased tolerance to a wide variety of environmental extremes including soil toxins, ionic concentrations, pH, and temperature (hot and cold). We shall elaborate briefly on two of the more important members of this list, nutrient relations and protection against root pathogens; and on one not on the list, water relations.

Water relations.--Although xylem potential of ectomycorrizal seedlings is often more negative than that of nonmycorrhizal seedlings during drought; photosynthesis, growth (particularly root growth) and survival is generally greater among those that are ectomycorrhizal (Dixon et al. 1980, Parke 1982, Sands and Theodorou 1978, Theodorou and Bowen 1970). Fungal species differ in their ability to confer drought resistance on a host. In Parke's (1982) study only one of four ectomycorrhizal species (Laccaria laccata) prevented weight loss of Douglas-fir seedlings subjected to artificial drought. Surprisingly, Laccaria laccata had relatively low drought tolerance when grown in pure culture. Duddridge et al. (1980) showed that rhizomorphous ectomycorrhizae grew to exploit moist soil when that around seedling roots dried, and suggested that these types would be the most effective in droughty soils.

Nutrient relations.--Ectomycorrhizae enhance nutrient uptake through increased root surface area; however, other, more active, mechanisms are also involved. Several studies have shown that ectomycorrhizal fungi release acid phosphatase, which catalyzes the hydrolysis of organic phosphates and thus plays a significant role in the phosphorus cycle (Alexander and Hardy 1981, Bartlett and Lewis 1973, Ho and Zak 1979, Williamson and Alexander 1975). Ho and Zak (1979) found that species differed markedly in their ability to produce this enzyme, however. Ectomycorrhizal fungi release various chelating agents, such as oxalate ions (Graustein et al. 1977) and hydroxamate siderophores (Powell et al. 1980), which are especially important in iron nutrition and perhaps in resistance to pathogens. Graustein et al. (1970) suggested that oxalate crystals adhering to ectomycorrhizae may act as chemical weathering agents. The biochemical repertoire of ectomycorrhizae, much of which we do not yet know, could represent a considerable advantage to trees in their competition with belowground organisms for nutrients.

Nitrogen (N) is the most limiting element in many forest ecosystems, however, the role of ectomycorrhizae in N nutrition of trees is poorly understood. N uptake is probably enhanced in ectomycorrhizal as opposed to nonectomycorrhizal trees simply because of increased root surface area. Because of competition for mineralized nitrogen, it would be a considerable additional advantage to trees if ectomycorrhizae were capable of decomposing organic matter, and thus could cycle N directly to the host tree. Went and Stark (1968) hypothesized that ectomycorrhizae indeed did this; however, Lundeberg (1970) concluded from his own and other studies that, while ectomycorrhizal fungi have some of the enzymes necessary for decomposition, they are generally at much lower levels than in those fungi that decompose organic material as a primary energy source.

Lundeberg (1970) found that ectomycorrhizal species differed in decomposing ability; however, the greatest variation he found was within species. Some isolates of several species produced decomposing-enzymes at a level similar to that of litter decomposing fungi, raising the possibility that a rich source of genetic variation exists from which highly efficient ectomycorrhizal strains can be selected.

As in litter decomposing ability, ectomycorrhizal fungi vary in their ability to utilize various N sources. Almost all species that have been tested grow better when N is supplied as ammonium rather than nitrate (Lundeberg 1970). About half the species which Lundeberg tested readily utilized some amino acids, particularly glycine and L-asparagine.

Protection against root pathogens.--Marx and Krupa (1978) make an impressive case for the protective effect of ectomycorrhizae. Pisolithus tinctorius has been shown to increase the survival of loblolly pine growing with the root pathogen Rhizoctonia solani (Wingfield 1968), and to protect both shortleaf pine and sand pine seedlings against the pathogen Phytophthora cinnamoni (Ross and Marx 1972, Marx 1973). Cenoccocum geophilum also protects shortleaf pine from P. cinnamoni (Marx 1973). Suillus granulatus prevents stunting and chlorosis caused in black spruce by the pathogen Mycelium radicus atrovirens (Richard et al. 1971). More recently, Sinclair et al. (1982) showed that Laccaria laccata was as effective as benomyl fungicide in protecting Douglas-fir seedlings against the root pathogen Fusarium oxysporum. How ectomycorrhizae protect against pathogens has not been conclusively demonstrated, but the protection probably involves various mechanisms, including physically barring root penetration by the pathogen, excreting antibiotics, inducing antipathogenic, chemical changes in the host, and stimulation of an inhibitory rhizosphere microflora (Marx 1972, Marx and Krupa 1978, Zak 1964). At least some ectomycorrhizal fungi can deactivate phytotoxins which tend to accumulate from various sources in many soils (Zak 1971). DeBell (1970) suggested that buildup of phytotoxins could reduce tree growth and reforestation success.

INTERACTIONS BETWEEN TREES AND SOME NONMYCORRHIZAL SOIL MICROBES

Nonmycorrhizal soil microorganisms influence tree growth in numerous ways. We shall briefly discuss one, protection from soil pathogens, that has received little attention in forestry.

It is a common observation that soils in some areas suppress pathogens. This phenomenon is primarily known in agriculture, but can also occur in forest soils. For example, both Broadbent and Baker (1974) and Halsal (1978) identified forest soils in New Zealand that suppressed the root-pathogen Phytophthora cinnamoni. Suppressive soils are either "natural" or "induced" (Schroth and Hancock 1982). Natural suppression results from soil chemical and physical characteristics which in turn determine composition of the microbial community. Induced suppression results from cultural practices or cropping sequence. As Schroth and Hancock (1982) point out, suppression is relative rather than absolute, and soils may exhibit a wide spectrum of behavior.

Although chemical and physical factors may play a role in suppression of pathogens in some soils, it appears to be primarily a biological phenomenon. Schroth and Hancock (1982) cite several cases in which soils were rendered conducive to disease through disruption of the native microflora. The biology of pathogen-suppression is far from clear, and probably varies among soils. Various organisms may inhibit pathogens. Among bacteria, species in the genera Bacillus, Pseudomonas, and Streptomyces have been reported to have mycolytic properties. Rose et al. (1980) isolated a species of Streptomyces from the rhizosphere of snowbrush (Ceanothus velutinus) that was antagonistic to three pathogens, Phellinus weirii, Fomes annosus, and Phytopthora cinnamomi. As we will discuss in greater detail later, the proportions of Streptomyces species that inhibit pathogens in forest soils vary from site to site and may be altered by soil disturbance.

Some nonmycorrhizal fungi inhibit pathogens. Species of the genus Trichoderma have been extensively studied in this respect, and have been shown in numerous experiments to protect agricultural plants against damping-off fungi (Chet and Baker 1980, Elad et al. 1980, Hadar et al. 1979, Henis et al. 1978, Wells et al. 1972). Kelly (1976) showed that Trichoderma harzianum reduced the incidence of damping-off in shortleaf pine seedlings.

Recently, attention has turned to the role of iron chelate-producing bacteria in disease suppression. Agronomists have known for some time that certain bacteria, appropriately called Plant-Growth-Promoting-Rhizobacteria (PGPR) (Schroth and Hancock 1982), stimulate plant growth. It has recently been demonstrated that at least some PGPR--members of the Pseudomonas group--produce and secrete iron chelators with a very high affinity for Fe (III) (Kloepper et al. 1980). Evidence suggests that these chelating agents, molecules of a generalized high-affinity Fe (III)-chelating group called siderophores, sequester iron in such a way that it is unavailable to pathogenic organisms (Kloepper et al. 1980). Siderophores are produced by numerous microorganisms (Szaniszlo et al. 1981). Hydroxymate siderophores (HS), a, class of siderophore produced primarily by fungi (including mycorrhizal fungi) are ubiquitous in soils (Powell et al. 1980). We shall show in a later section that HS production is reduced in many logged areas, and that this may impact seedling growth.

MANAGEMENT IMPACTS ON SOIL BIOLOGY

Ectomycorrhizae

Impacts of clearcutting and site preparation on ectomycorrhizal fungi vary with fungal species, site preparation (burning, windrowing, etc.), and probably with site. Ectomycorrhizae are, at least

in some studies, predominantly found in soil organic layers (Harvey et al., this volume), thus removal of organic material though burning or windrowing tends to reduce ectomycorrhizal formation on seedlings. Wright and Tarrant (1958) found fewer ectomycorrhizae on Douglas-fir seedlings grown in burned areas than on those grown in unburned areas. Greatest reductions were associated with the hottest burns. Harvey et al. (1980) found that slash burning reduced mycorrhizal activity for at least 7.6 m into an adjacent, uncut stand. Parke (1982) compared mycorrhizal formation on 36 "difficult to regenerate" clearcuts in northern California and southwest Oregon. Douglas-fir and ponderosa pine seedlings grown in soils from burned clearcuts formed 40 percent fewer ectomycorrhizae than seedlings grown in undisturbed forest soil, and seedlings grown in soil from unburned clearcuts formed 20 percent fewer. Potential for ectomycorrhizal formation appears to vary with clearcut age. Parke (1982) found no reduction in ectomycorrhizae on seedlings grown in soils from clearcuts less than 2 years old; nor did Pilz and Perry (1983) when studying recent clearcuts in the Oregon Cascade Range.

Some evidence suggests that sites with diverse fungal populations may be buffered against declines in ectomycorrhizal potential following disturbance. Schoeneberger and Perry (1982) studied sites in the Cascade range in Oregon that had been disturbed to different levels. Ectomycorrhizal formation on Douglas-fir was highest in soils from a logged, unburned area, and lowest in soil from one undisturbed forest, a result of litter leachates acting on a major ectomycorrhizal type. In contrast, ectomycorrhizae on western hemlock were lowest in soils from a recent clearcut that had been burned and a plantation that had been clearcut and burned 20 years previously, primarily because of reductions of Cenococcum geophilum in the burned areas. Both Douglas-fir and western hemlock formed five to six mycorrhizal types in all soils. The proportions of each type, however, changed significantly with soil disturbance level; suggesting that, like higher plants, ectomycorrhizal fungi are differentially adapted to disturbance. Relative stability of ectomycorrhizal fungi following disturbance may be an important factor in the ability of trees to successfully recolonize disturbed sites.
In contrast to the Oregon sites of Schoenberger and Perry (1982), soils from the Montana areas studied by Perry et al. (1982) yielded only one ectomycorrhizal type on Douglas-fir, lodgepole pine, and Engelmann spruce seedlings. Seedlings of all species formed significantly more ectomycorrhizae in soil from undisturbed forest than in soil from clearcut areas, regardless of slash treatment (burning, windrowing, or neither). This study is not directly comparable to that of Schoenberger and Perry (1982) because Montana clearcuts were substantially older than most of those in Oregon. Nevertheless it is reasonable to hypothesize that, because of low fungal diversity, ectomycorrhizal potential in Montana soils was poorly buffered against disturbance.

In the two studies discussed above, Oregon sites were characterized by a mesic, oceanic-influenced climate and, judging from the timber volume present in undisturbed forest, were highly productive. Montana sites, in contrast, had a harsh, continental climate and low productivity. Differences in fungal diversity between the two areas may be related to differences in climate and productivity; however, more research must be done on this point. If so, we should expect ectomycorrhizal formation on productive sites to, in general, be better buffered against disturbance than that on sites with relatively low productivity.

What causes reductions in ectomycorrhizal formation on disturbed sites? Inocula are likely to be reduced through physical removal or destruction (burning, windrowing), host-removal (clearcutting), or because the habitat for small mammals--important vectors for hypogeous fungal spores (which are not wind distributed)--is destroyed (Maser et al. 1978). Inocula is undoubtedly a factor in reductions of ectomycorrhizae, but two lines of evidence suggest that it is not the entire story. First, a little inocula can go a long way. For example, Pilz and Perry (in press) found no difference in numbers of ectomycorrhizae formed on Douglas-fir grown in pasteurized soils amended 1:10 with nonpasteurized soil and those grown in nonpasteurized soil, although the latter presumably had about 10 times more inocula. Secondly, reduction in ectomycorrhizal formation is often accompanied by reduction in total numbers of root tips (e.g., Perry et al. 1982). Thus it is difficult to judge whether fewer ectomycorrhizae form because the seedling produces fewer tips or vice versa.

In at least some cases, production of root tips can be altered by soil pasteurization, suggesting influence by biological factors. Figure 1 shows total root tip formation (ectomycorrhizal plus nonectomycorrhizal) on the previously discussed Montana site (Perry et al. 1982) and on three sites in southern Oregon that have not been reported on. Experimental procedure for the three southern Oregon sites was as follows. In each site soil was collected to a depth of 25 cm from five randomly located plots each in logged and burned, logged and unburned, and adjacent undisturbed areas. The five samples from each disturbance type were combined and mixed to give a composite sample of about 5,000 g soil/site. The soil was returned to the laboratory and sifted through a 2-mm screen. Moisture content was determined by drying a 20 g subsample at 60°C until a constant weight was reached. Soil was analyzed by the Soil Testing Laboratory, Oregon State University (for PO_4, Ca, Mg, NH_4, NO_3-N) and the Forestry Sciences Soil Testing Laboratory (for S and N). Organic carbon was determined by combustion methods and analyzed on a LECO Carbon Analyzer. Nitrogen was determined by micro-Kjeldahl methods (Jackson 1958); extractable Mg and Ca were determined by atomic absorption spectrophotometric techniques; available phosphorus was determined by the sodium bicarbonate extraction technique (Watanabe and Olsen 1965); and soil pH was measured from a water saturation paste on an Orion pH meter. Soil characteristics are given in table 1. A subsample of soils was steam-pasteurized for 3 hours at 100°C, allowed to cool 24 hours, pasteurized again

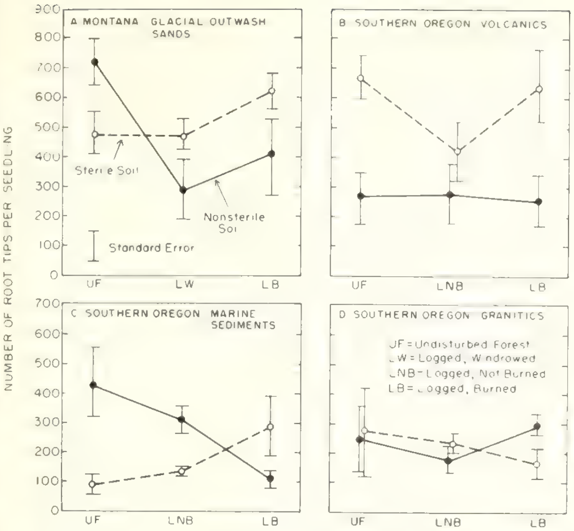

Figure 1.--Greenhouse bioassays of root-tip development on Douglas-fir seedlings grown in soils from disturbed and undisturbed sites in Montana and Oregon. Each figure (A-D) represents an assay of soil from a single set of logged and unlogged sites; there is no replication of substrate type. Data for Montana glacial outwash stands is from Perry et al. (1982).

for 3 hours, allowed to cool 24 hours, then pasteurized for a final 3-hour period. Ten Douglas-fir seed were planted per site-treatment combination, grown for approximately 5 months, then lifted. Total root tips per seedling were counted with a dissecting microscope. Error bars in figure 1 are based on the 10 seedling-replicates.

Among the four sites shown in figure 1 there were three different response patterns. On two of the southern Oregon sites, seedling root tip formation was not affected by logging or logging and burning, and soil pasteurization had a variable effect. In the Montana glacial outwash sands and soils of the southern Oregon sites, seedling root tip formation was not affected by logging or logging and burning, and soil pasteurization had a variable effect. The Montana glacial outwash sands and southern Oregon marine sediments shown in figure 1a and 1c are particularly intriguing. On these sites sterilization of soils in which Douglas-fir seedlings formed relatively large numbers of root tips (undisturbed soil in Montana and Oregon and clearcut-unburned soil in Oregon) lowered root tip formation; while sterilization of soils with relatively low "root tip potential" (clearcut and either burned or windrowed) increased root tip formation. Pasteurization alters physical as well as biological soil factors; however, in subsequent work we have determined that pasteurized soils that are reinoculated with small amounts of unpasteurized soil tend to produce results intermediate between pasteurized and nonpasteurized soils, suggesting that at least part of the pasteurization effects shown in figure 1 are due to reduction or elimination of soil organisms. Thus it seems possible that on these sites, burning or, in Montana, windrowing, altered the soil biota from one that facilitates to one that inhibits root tip production. As we shall see in the next section, the microbial community is altered dramatically by soil disturbance, particularly burning; however, it is not clear how, or even if, this impacts root tip production. Widely varying responses among sites (figure 1) suggest that considerable research may be needed to understand the mechanisms involved.

Nonmycorrhizal Biota

Ahlgren (1974), Harvey et al. (1976), and Wells et al. (1979) recently reviewed the effects of fire on soil organisms. In most cases, fire immediately reduces populations of bacteria, fungi, and actinomycetes, though the latter seem most resistant (Ahlgren 1974, Dunn et al. 1979). Recovery is accompanied by changes in species composition that may persist for decades. Nitrifying bacteria are especially sensitive to heat. Dunn et al. (1979) found that fungi recovered more

Table 1--Soil characteristics of southern Oregon sites (Siskiyou National Forest)

Substrate and treatment	PO_4 ppm	Ca meq	Mg meq	C %	S %	Total N %	C/N	NH_4 ppm	NO_3 ppm	pH
Granitic										
Undisturbed	11	7.5	0.71	4.3	0.04	0.25	17:1	12.2	4.5	5.16
Logged and unburned	37	12.5	.75	2.2	.02	.29	8:1	5.8	4.2	5.85
Logged and burned	33	8.2	.36	3.9	.02	.26	15:1	5.0	3.0	5.97
Volcanic										
Undisturbed	104	11.0	2.5	6.1	.02	.22	28:1	7.9	.34	5.62
Logged and unburned	115	11.0	2.0	6.0	.02	.22	27:1	8.3	.63	5.71
Logged and burned	75	11.2	1.5	3.9	.02	.14	28:1	5.8	.80	6.27
Marine sediments										
Undisturbed	21	4.5	1.4	6.2	.17	.22	28:1	9.7	.30	4.68
Logged and unburned	63	7.3	1.1	6.0	.21	.23	26:1	8.8	.50	5.16
Logged and burned	80	16.0	1.4	4.0	.15	.23	17:1	10.5	.90	6.16

quickly than heterotrophic and nitrifying bacteria in burned chapparal soils.

Fungal species vary widely in their response to burning. Widden and Parkinson (1975) reported that some species of *Trichoderma* and *Penicillium*, important because of their antagonism to pathogenic fungi, were inhibited by leachate from burned litter and were thus unable to recolonize upper soil layers after forest fire. *Cylindrocarpon destructans*, a potential pathogen, was unaffected, and Widden and Parkinson suggested that this shift in fungal species might produce increased incidence of disease in planted seedlings. Lucarotti *et al*. (1978) found that some species of *Trichoderma* and *Penicillium* occurred frequently in the soil of a site burned 2 years previously, whereas others did not. (Later we will discuss evidence that increased pathogenesis does indeed occur in some disturbed soils.)

With some exceptions (e.g., nitrifiers), bacteria are more heat tolerant than fungi (Wells *et al*. 1979) and are generally better adapted than fungi to high pH soils (Ahlgren 1974). Most studies show that the ratio of bacteria to fungi increases sharply after fire. Fire often increases soil pH for a period, and this may account for gains in bacterial numbers relative to fungi.

Table 2 shows the numbers of various microfloral types in the southern Oregon soils described earlier (table 1). To estimate the number of microflora, triplicate soil dilutions of 20 g each were plated on sodium albuminate agar (pH 6.8), a selective medium for *Streptomyces* and non-filamentous bacteria, and Rose Bengal Agar, a selective medium for fungi (Johnson *et al*. 1965). Colonies of fungi were counted after 4-days incubation at 28°C, and bacteria and *Streptomyces* after 8-days incubation at 28°C. Burning had a minor effect on fungal numbers, but bacterial numbers increased sharply on all burned areas. Actinomycetes varied in somewhat the same pattern as bacteria, but less dramatically. Differences between 1980 and 1981 are probably due to rainfall patterns.

Changes in soil microflora may affect site productivity in two ways: first, by altering patterns of chemical conversion and decomposition, which in turn affect nutrient availability to plants and nutrient retention within the soil (we shall not deal with this further); and second, by altering the balance between pathogens and organisms which inhibit pathogens. In some cases burning has resulted in a high incidence of pathogenesis on tree seedlings, as suggested by Widden and Parkinson (1975). Germination of spores and growth of mycelia of the root rot *Rhizina undulata* are stimulated by heat and heated extracts of pine roots (Julaluddin 1968 cited in Ahlgren 1974); in Finland postfire plantations of Scots pine (*Pinus silvestris*) and Muhgo pine (*Pinus mugo*) are commonly infected by this fungus (Laine 1968 cited in Ahlgren 1974). Further, some microfloral types, though not pathogenic, may release chemicals that inhibit tree seedlings and mycorrhizal fungi. Table 3 shows the percentage of *Streptomyces* sp., isolated from the southern Oregon soils of table 1, that inhibit growth of the pathogen *Phellinus weirii* or the ectomycorrhizal fungus *Laccaria laccata*. A cross-inoculation assay method (Johnson and Curl 1972) was used to test for antagonism of *Streptomyces* spp. to *Phelinus weirii*, and *Laccaria laccata*. In this method the test organism was inoculated on a malt-yeast-peptone agar plate for *P. weirii* (Hutchins 1980) opposite a culture of *P. weirii*; a buffered MN agar was used to test mycorrhizal fungal-*Streptomyces* antagonistic response. Plates were incubated at 26°C for 2 to 3 weeks and inspected for a clear zone around the *Streptomyces* colony, indicative of antibiosis. Approximately 150 randomly selected *Streptomyces* colonies from each site were isolated and tested for antagonism to pathogenic and mycorrhizal fungal species. On one site (granitic substrate) antagonism to *Phellinus weirii* was greater among *Streptomyces* isolated from disturbed soils than among those isolated from undisturbed soil, and on all sites there was an increase in antagonism to *Laccaria laccata* on disturbed areas. These preliminary results suggest further research would be warranted.

Table 2--Numbers of bacteria, actinomycete, and fungal colonies per gram of dry soil, for undisturbed, logged and unburned, and logged and burned areas of three different sites in southern Oregon

Substrate and treatment	1980 Soil collections			1981 Soil collections		
	Bacteria	Actinomycetes	Fungi	Bacteria	Actinomycetes	Fungi
	Millions per gram dry soil					
Granitic						
Undisturbed	0.62	1.02	0.18	3.3	2.3	0.10
Logged and unburned	1.12	.76	.23	2.7	3.8	.12
Logged and burned	3.93	.94	.12	4.9	4.6	.08
Volcanic						
Undisturbed	.31	1.01	.14	4.67	2.79	.16
Logged and unburned	.44	.70	.13	6.55	3.38	.17
Logged and burned	2.87	1.63	.16	12.64	4.31	.12
Marine sediments						
Undisturbed	.39	.64	.16	2.26	2.86	.15
Logged and unburned	.61	.55	.21	1.96	2.28	.21
Logged and burned	2.88	1.25	.16	7.53	1.91	.11

Table 3--Percentage of Streptomyces sp., isolated from various southern Oregon soils, that inhibit growth of the pathogen Phellinus weirii or the ectomycorrhizal fungus Laccaria laccata

Substrate and treatment	Percent of Streptomyces isolates antagonistic to Phellinus weirii	Laccaria laccata
	------------%------------	
Granitic		
Undisturbed	7	18
Logged and unburned	22	20
Logged and burned	47	30
Volcanic		
Undisturbed	11	8
Logged and unburned	17	26
Logged and burned	12	39
Marine sediments		
Undisturbed	36	22
Logged and unburned	31	46
Logged and burned	25	26

Earlier we mentioned siderophores, microbially produced iron chelators that may play a role in protecting higher plants against pathogens as well as being directly involved in iron nutrition. Perry et al. (in press) measured siderophores in soils from 10 widely scattered sites in southwest, central, and east-central Oregon. On 8 of the 10 logged sites, siderophore concentrations were reduced in burned soils (table 4). To test whether reduced siderophores affected the iron nutrition of tree seedlings we grew Douglas-fir in burned and in undisturbed soils that were (1) steam pasteurized, (2) amended with iron, or (3) neither (controls). Seedlings grown in nonsterile, undisturbed soils did not respond to iron fertilization (figure 2a,b). Pasteurization of undisturbed soils lowered seedling growth, but this could be reversed by adding iron, suggesting that some component of the soil biota--possibly the siderophore producers--are important in the iron nutrition of Douglas-fir seedlings. Top growth of seedlings in nonsterile, burned soils was lower than that of seedlings grown in nonsterile undisturbed soils. The difference was eliminated by iron fertilization, however, further implicating siderophores as important in the iron nutrition of seedlings grown in these particular soils. The fact that seedlings grown in sterile, burned soil did not respond to iron fertilization may indicate that an intermediate, biologically mediated step is necessary to translate added iron to seedling growth in the burned soil, however, more research is needed.

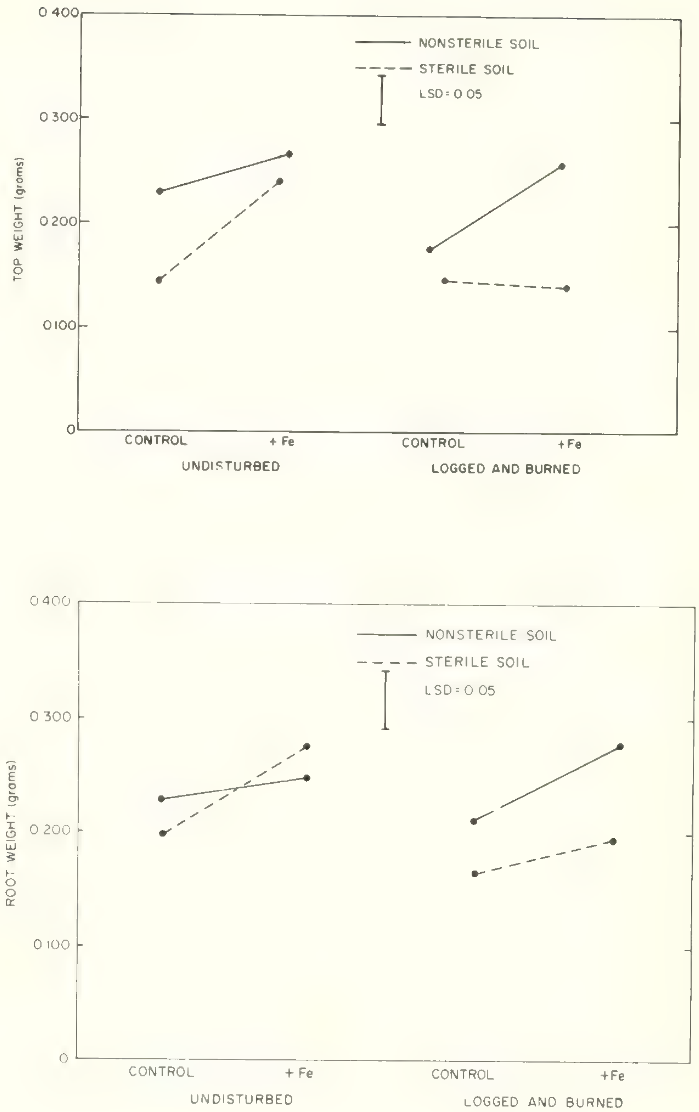

Figure 2.--Effect of iron fertilization and soil sterilization on growth of Douglas-fir seedlings in undisturbed soils (high siderophore concentration) and burned soils (low siderophore concentration) on one Oregon site (Perry et al. in press). a. Top growth. b. Root growth.

SOIL BIOTA AS A SILVICULTURAL TOOL

Schroth and Hancock (1982), discussing the role of PGPR in growth of agricultural crops, state "...it has now been demonstrated that the root microflora can be altered qualitatively and quantitatively and that this can lead to substantial increases in yield." This statement should apply equally well to forest crops. Important advances have been made in the silvicultural use of soil microbes. Enhanced survival and yield of tree seedlings inoculated with the ectomycorrhizal fungus Pisolithus tinctorius (Marx and Krupa 1978 review the literature) are the best example. The generally disappointing performance of P. tinctorius in the Pacific Northwest (e.g., Alvarez 1982), however, suggests that no single organism may be appropriate for all sites. The wide degree

Table 4--Hydroxymate-siderophore concentrations (± SE) in various disturbed and adjacent undisturbed forest soils in Oregon. Means that have different superscripts in any one row are significantly different at the 0.05 level (from Perry et al., in press).

Site	Concentration (μg/ml Desferal equivalent)		
	Undisturbed	Logged-burned	Logged-unburned
Southwest Oregon; 1, 2, 3	11.05^{a} ± 2.14	1.45^{b} ± 1.74	4.11^{b} ± 1.18
4	1.62^{a} ± 0.23	0.20^{b} ± 0.19	--
West-central Oregon; 1	2.27^{a} ± 0.37	1.45^{a} ± 0.30	--
2	0.12^{a} ± 0†	0.08^{a} ± 0.04	0.25^{b} ± 0.03
East-central Oregon; 1	0.19^{a} ± 0	--	0.21^{a} ± 0.47
2	1.09^{a} ± 0.16	0.19^{b} ± 0.13	--
3	0.87^{a} ± 0.06	0.16^{b} ± 0.05	--
4	1.18^{a} ± 0.21	0.55^{b} ± 0.17	1.10^{a} ± 0.18

†Two replicates.

of genetic variability between, and especially among species of mycorrhizal fungi, represents a vast, untapped, silvicultural potential.

Many of the yield-enhancing attributes of soil microbes appear to be the product of complex co-evolutionary relationships within natural ecosystems. One important key to silvicultural use of soil biology, as in other silvicultural tools, is understanding, protecting, and intelligently utilizing the often complex and highly variable mechanisms that have evolved in natural ecosystems.

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EFFECTS OF SOIL ORGANIC MATTER ON REGENERATION IN NORTHERN ROCKY MOUNTAIN FORESTS

A.E. Harvey, M. F. Jurgensen and M. J. Larsen

ABSTRACT: Successful establishment, strong ectomycorrhiza development and good growth of natural conifer regeneration in three old-growth forests of western Montana required a predominantly organic rooting medium. This requirement was most evident with establishment of seedlings in decayed wood on the driest site. Responses of natural seedlings to organic soil components were also observed on one of two similar but disturbed sites.

INTRODUCTION

Research has demonstrated positive relationships between various organic components of forest soils in the central and northern Rocky Mountains and the ability of conifers to support high populations of active ectomycorrhizal root tips in old-growth forests (Harvey et al., 1979, 1980a and 1981). Day (1963) reported that high populations of conifer seedlings became established on organic seedbeds on harvested sites in the Rocky Mountains of Canada and Minore (1972) has shown several West Coast species can utilize organic seedbeds. This suggests that various rooting activities of conifer seedlings, at least under some conditions, are dependent on organic soil substrata.

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This report documents relationships between various soil organic components and roots of natural regeneration of several northern Rocky Mountain conifers. It also shows the effect of changed soil environments following timber harvesting on those relationships.

METHODS

The five experimental sites reported on here were located in northwestern Montana in the vicinity of Glacier National Park. The undisturbed sites were located within the boundaries of the Coram Experimental Forest and the disturbed sites in the Miller Creek drainage approximately 20 miles northwest of the Experimental Forest (DeByle 1981). The timber type in all cases is Douglas-fir/larch. Elevations range from 1 018 m to 1 942 m above sea level. Mean annual precipitation is 78.7 cm and mean annual temperature, 5.3°C. Mean annual summer temperatures average 16.1°C.

Site 1 is an undisturbed, 250-year-old forest on a warm, dry, south slope dominated by Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco). Site 2 is an undisturbed, 250-year-old forest on a cool,

moist, east slope dominated by Douglas-fir, western Larch (Larix occidentalis Nutt.) subalpine fir (Abies lasiocarpa [Hook] Nutt.), and Englemann spruce (Picea engelmannii Parry ex Engelm.). Site 3 is a warm, moist, north slope dominated by western hemlock (Tsuga heterophylla [Raf.] Sarg.), and sites 4 and 5 are similar to site 2, except they are an August-burned, west-slope and October-burned, south-slope clearcutting, respectively, broadcast burned 14 years previously. The undisturbed sites are representative of Pseudotsuga menziesii/Physocarpus malvaceus (PSME/PHMA), Abies lasiocarpa/Clintonia uniflora (ABLA/CLUN), and Tsuga heterophylla/Clintonia uniflora (TSHE/CLUN) habitat types, respectively. The disturbed sites are representative of the Abies lasiocarpa/Clintonia uniflora habitat type, the same as site 2, but they have been classified in the Xerophyllum tenax phase, which is slightly more xeric than site 2 (Pfister et al. 1977).

Sampling consisted of removing natural, established, whole seedlings and determining root distribution patterns in the various soil substrates. Ten seedlings, regardless of species, were taken randomly from around 10 permanent plot centers evenly dispersed throughout each of the experimental sites. Sampling occurred in late June and early July of 1980 and 1981. This procedure provided 100 seedlings of mixed species from each site. Only seedlings considered likely to continue to survive were taken. In most cases this resulted in an age span of 4 to 8 years, depending on stand conditions.

Each seedling was lifted with a long-bladed spade to preserve the root system. The root ball was carefully dissected and the root system removed intact. The following data were recorded during the dissection process: species, seedbed characteristics (depth of moss, humus, soil wood and mineral soil in the surface 30 cm), nearest deposit of decayed wood (centimeters), distribution of the roots in each soil component (percent estimated) and the particular substrate (soil component) that supported 50 percent or more of the root system and ectomycorrhizae of each seedling.

RESULTS

The physical nature of soil microsites providing satisfactory conditions for establishment of natural conifer seedlings is presented in table 1. These data show substantial quantities of organic matter in the immediate environment of the seedlings from all three undisturbed stands, but not the two clearcut stands. The highest organic substrate was associated with seedling establishment on the driest, undisturbed site.

Table 2 shows the principal rooting substrate; i.e., the soil component containing most of the root system and ectomycorrhizae for seedlings naturally established on each of the five sites. These data clearly show that organic soil components provided an important substrata for seedling roots throughout a wide variety of environmental conditions, including one of the two clearcut and burned sites. The data indi-

Table 1--Average[1/] seedbed profile conditions associated with established seedlings at the experimental sites as indicated by depth of individual soil components

Soil component	Site 1 (PSME/PHMA)[2/] Undisturbed south slope	Site 2 (ABLA/CLUN) Undisturbed east slope	Site 3 (TSHE/CLUN) Undisturbed north slope	Site 4 (ABLA/CLUN) Clearcut-burn west slope	Site 5 (ABLA/CLUN) Clearcut-burn south slope
	- - - - - - -	- - - - - - -	(cm)	- - - - - - -	- - - - - - -
Moss	0.04[a][3/]	0.03[b]	0.04[c]	0.14[d]	0.12[e]
Litter	.62[a]	1.01[b]	1.29[c]	.30[d]	.29[d]
Humus	.58[a]	1.99[b]	2.90[c]	.30[d]	1.01[e]
Decayed wood	18.95[a]	6.62[b]	8.44[b]	.03[c]	.32[d]
Mineral soil in surface 30 cm	9.53[a]	20.39[b]	17.28[b]	28.96[c]	28.22[d]

1/ Average in this case is not indicative of a generalized soil condition on the site. Rather, it is a situation representing only successful establishment microsites for natural seedlings. For data on average soil conditions on sites 1, 2, and 3, see Harvey et al. (1979).

2/ Habitat type designation (Pfister et al. 1977).

3/ For statistical comparisons between sites, across rows to right, differing superscript letters indicate differences to at least α = .05 with t = test comparisons.

Table 2--Percentage of established, natural seedlings from each experimental site with more than 50 percent of their ectomycorrhizae and root systems in the respective soil component

Forest site and seedling species	Soil component: Moss	Humus	Decayed wood	Mineral
	- - - - - -	- - - - (percent)	- - - -	- - - -
Site 1 (PSME/PHMA)[1]			Undisturbed, south slope	
Douglas-fir	0	24	70	5
Western white pine	0	1	0	0
Site 2 (ABLA/CLUN)			Undisturbed, east slope	
Douglas-fir	0	31	22	0
Western white pine	0	0	1	0
Subalpine fir	0	18	20	5
Englemann spruce	0	0	2	0
Western hemlock	0	0	1	0
Site 3 (TSHE/CLUN)			Undisturbed, north slope	
Douglas-fir	0	7	1	1
Western hemlock	1	26	35	3
Western red cedar	7	15	2	1
Western larch	0	0	1	0
Site 4 (ABLA/CLUN)			Clearcut, August broadcast burn west slope	
Douglas-fir	0	0	0	70
Western larch	0	0	0	22
Englemann spruce	0	0	0	6
Lodgepole pine	0	0	0	2
Site 5 (ABLA/CLUN)			Clearcut, October broadcast burn south slope	
Douglas-fir	0	2	1	54
Subalpine fir	0	0	0	31
Englemann spruce	0	2	1	9

1/ Habitat type designation (Pfister et al. 1977).

cated that on the clearcut and burned sites, environmental conditions were such that organic soil components were relatively less important as rooting substrata for natural conifer seedlings.

DISCUSSION

The strong relationship between soil organic components and distribution of seedling roots in undisturbed stands is likely related to soil moisture content during the dry summer season. Earlier research by the authors indicated that ectomycorrhizal activity on these sites follows similar patterns and appears to be primarily a moisture-dependent phenomenon (Harvey et al. 1980a). In addition, the soil profiles in the proximity of seedlings from sites 1, 2 and 3 (as shown in table 1) had substantially greater quantities of organic matter than previously reported for random soil samples from these same sites (Harvey et al. 1979). In the case of the clearcutting, rooting patterns may also be a moisture-dependent reaction; however, we think further analysis will indicate that the harvesting and burning histories of the sites had differential effects on the quantity, type, distribution and condition of the soil organic matter, and that aspect may introduce strong variables not yet accounted for. Substantially increased soil moisture, as compared to established stands, was probably available to the seedlings on the clearcut sites.

Our major conclusion is that harvesting and site preparation procedures that alter the distribution, type and quantity of soil organic matter likely have the potential to control the survival, growth and species distribution of conifer seedlings. This effect is in addition to the potential for losses in longer term forest soil productivity if organic components are destroyed (Harvey et al. 1980b).

APPLICATION

Based on the variability in effectiveness of organic matter in supporting naturally established conifer seedling roots and the importance of soil organic matter to long-term forest soil productivity, we currently recommend site preparation and harvesting procedures for the northern Rocky Mountains that do not cause exces-

sive loss or disruption of soil organic components. We further suggest that site preparation methods that generate maximum seedling microsite variability will provide the best possible conditions for successful, natural seedling species. With the current poor state of knowledge on soil microsite-seedling relationships, this approach should provide at least some microsites highly suitable to available seed stock on any particular site in any given year.

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EFFECTS OF SITE PREPARATION ON PINUS ELLIOTTII-P. PALUSTRIS FLATWOODS FOREST SOIL PROPERTIES

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ABSTRACT: Results from three investigations in Pinus elliottii Engelm.-P. palustris Mill. flatwoods ecosystems were used to evaluate the effects of minimal disturbance and intensive methods of preplanting site preparation on physical, chemical and biological soil properties. Organic matter and nutrient concentrations of the mineral soil were only slightly altered by site preparation; however, forest floor nutrient storage was severely reduced in the intensively prepared (windrowed) plantations. Nitrogen, P, K, Ca and Mg contents of the forest floor were 19, 1, 1, 8 and 2 kg/ha, respectively, in the intensively prepared plantations. Storage of these nutrients in undisturbed forests and minimally disturbed plantations was at least ten times greater.

Surface soil bulk density of intensively prepared plantations was slightly greater (0.1 g/cm^3) than bulk density in minimally prepared plantations or undisturbed forests. Maximum soil temperatures at 10-cm depth were increased from 24^{o}C in the undisturbed forest to 28^{o}C and 32^{o}C in the minimally and intensively prepared plantations, respectively. Surface soils of intensively prepared plantations were subject to larger moisture fluctuations and tended to be drier than the surface soils in either minimally prepared plantations or undisturbed forests.

Increased soil temperatures and more pronounced wetting and drying cycles accelerated N mineralization in intensively prepared plantations. This accelerated mineralization appeared to cause a reduction in mineralizable N contents of the surface soil by the second growing season.

INTRODUCTION

The Pinus elliottii Engelm.-P. palustris Mill. flatwoods forests[1/] of the southeastern coastal plain are among the most intensively managed forests in the United States. Low relief and large ownerships combine to make these lands favorable for mechanized operations and intensive plantation management.

Soils supporting flatwoods forests are developed in Pleistocene deposits of marine sand. Although areas of well-drained soils occur, the most common soils are poorly drained spodosols and somewhat poorly drained ultisols. These soils contain few weatherable minerals, and reserves of all major plant nutrients are low.

The benefits of preplanting site preparation of flatwoods areas are well established. Early attempts to replant cutover areas without site preparation often resulted in plantation failure. Mechanical site preparation was introduced in the mid-1950s in an effort to simulate conditions of old fields where plantations were more easily established. These attempts proved successful

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1/The term "flatwoods" has been used to describe a variety of landscapes. In this paper, flatwoods refers to landscapes in northern Florida and southern Georgia described by McCulley (1950). These areas are characterized by a mixed P. elliottii-P. palustris overstory and a wire grass (Aristida spp.), gallberry (Ilex glabra [L.] Gray), and palmetto (Serenoa repens [B.] Small) understory. Very poorly drained cypress (Taxodium distichum [L.] Rich.) or hardwood ponds occupy 25-30 percent of the area.

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and mechanical site preparation was being used on an operational scale by 1960 (Wilhite 1961). The size of the equipment and sophistication of site preparation operations have evolved since then, and there are now five common methods of mechanical site preparation: chopping, shearing, piling (with either a blade or rake), harrowing and bedding. These methods are typically used in combination with each other, or with other cultural practices such as burning, herbicide application, or fertilization, to form a complete site preparation operation.

During the last decade, concern that some methods of intensive site preparation could lead to declines in productivity of flatwoods sites has increased. Most of this concern has focused on the effects of accelerated nutrient drain from these nutrient-poor ecosystems (Bengtson 1981; Haines et al. 1975; Hollis et al 1979); however, deterioration of soil physical properties has also been implicated. This paper examines the impacts of minimal disturbance and intensive site preparation methods on physical, chemical and biological properties of surface soils in young P. elliottii plantations. Potential effects of soil changes on future site productivity are discussed.

INFORMATION BASE

The effects of intensive site preparation on forest soil properties have been evaluated in three studies of P. elliottii-P. palustris flatwoods in north central Florida. General experimental conditions of each of these investigations are presented in table 1. Detailed descriptions of the study sites and methods are available in the references listed in table 1 and will not be repeated in this paper.

Many similarities existed among the three studies. Each study included minimal-disturbance site preparation consisting of chop-only or chop-and-bed operation as one treatment, and an intensive site preparation which included a KG-blading (windrowing) operation as a second treatment in the experimental design. A third undisturbed area was left as a control. Forest floor and soil samples were collected from interbed (or nonbedded) areas of the young plantations and from undisturbed control sites to avoid the confounding effect of topsoil localization associated with bedding operations. Soil samples were analyzed for bulk density, reaction, organic matter concentration, cation exchange capacity, total N, aerobically mineralizable N, and double acid extractable P, K, Ca, and Mg concentrations. Total nutrient contents of the forest floor were also determined. Soil water samples were periodically collected and analyzed for NH_4-N and NO_3-N concentrations. Soil temperature, soil moisture, and water table elevations were recorded during the first growing season of the young plantations.

RESULTS AND DISCUSSION

Harvest and site preparation influence soil properties both directly (through soil disturbance and nutrient removal) and indirectly (through microclimatic changes). Because few controlled experiments have been monitored long enough to yield meaningful growth results, the effects of these changes on long-term productivity can only be speculated. Although speculations of this nature have shortcomings, they are valuable for anticipating trends.

Table 1--Summary of experimental conditions in three studies on the effects of site preparation on forest soil properties

Designation	Location	Soil type	Treatments: Minimal disturbance	Treatments: High intensity	Treatments: Undisturbed control	References
Owens-Illinois Pfifer Tract	Alachua County, Florida	Basinger fine sand (spodic Psammaquent)	Double chop	KG-blade and bed	23-year-old P. elliottii	Pritchett and Wells (1978); Pritchett and Morris (1982)
Austin Cary Forest	Alachua County, Florida	Electra (Arenic Ultic Haplohumud) and Wauchula (Ultic Haplaquod) fine sand	Chop and burn	Burn, KG-blade, disk harrow and bed	Naturally regenerated 40- to 45-year-old P. elliottii-P. palustris flatwoods forest	Burger (1979)
Bradford Forest	Bradford County, Florida	Mascotte (Ultic Haplaquod) and Stilson (Arenic Plinthic Paleudult) fine sand	Chop and bed	Stump, burn, KG-blade, disk harrow and bed	Naturally regenerated 40-year-old P. elliottii flatwoods forest	Morris (1981); Morris and Pritchett (1982)

Table 2--Comparison of chemical properties of surface soil horizons (A or Ap) beneath undisturbed flatwoods forests with soil properties in 1-year-old *P. elliottii* plantations

Site preparation	Organic matter	CEC	pH	C/N ratio	Total N	Extractable P	Extractable K	Extractable Ca	Extractable Mg
	%	meq/100g			%	ppm	ppm	ppm	ppm
Austin Cary Forest[1]									
Undisturbed[2]	1.5	2.27	4.3	31	0.03	2.5	15	16	12
Minimal disturbance	1.9	2.46	4.4	28	.04	3.4	17	83	25
Intensive	1.2	1.72	4.5	24	.03	2.6	15	53	17
Treatment effect[3]					*			*	*
Bradford Forest[4]									
Undisturbed	5.2		4.4	38	.08	1.7	17	122	53
Minimal disturbance	5.2	N.D.	4.5	38	.08	1.6	18	117	59
Intensive	4.4		4.3	37	.07	1.1	19	111	40
Treatment effect									

1/ Source: Burger (1979)
2/ Mean for preharvest analyses
3/ Indicates significant differences between at least two means
4/ Source: Morris (1981), Mascotte soil

Effects on Soil Chemistry

Volatilization of N during burning and displacement of organic debris and mineral soil into windrows during KG-blading of intensively prepared sites would be expected to reduce nutrient concentrations and contents of the surface soil. Morris et al. (1983) calculated that KG-blading removed 180 t/ha of slash, litter and soil material from the intensively prepared Bradford Forest site. This material contained 373, 18, 27, 163 and 41 kg/ha of N, P, K, Ca and Mg, respectively. Despite such substantial nutrient removals, differences in chemical characteristics of mineral soil in intensively prepared sites were difficult to detect (table 2). Small reductions in soil organic matter and concentrations of N, P, Ca and Mg were observed on the intensively prepared Austin Cary and Bradford Forest sites, but these differences were seldom statistically significant. Large reductions in nutrient content were confined to the forest floor and residual slash components of intensively prepared sites (table 3). Although no reduction in forest floor weight occurred on minimally disturbed sites, nutrient contents were slightly lower. Surface additions of coarse wood material during logging, coupled with accelerated decomposition of finer and more nutrient-rich litter materials, were probably responsible for this reduction.

Studies of site preparation by Haines and Pritchett (1965) and Shultz (1976) have also failed to detect large differences in mineral soil chemistry following site preparation of varying intensities[2]. Apparently, mineralization and transfer of nutrients from residual slash (table 3) to the soil proceeds too slowly to measurably alter soil chemistry of minimally prepared sites. Enough mixing of fertile with infertile soil occurs during windrowing of intensively prepared sites to offset any large downward bias in soil nutrient concentrations.

Changes in Physical Properties

Compaction.--Soil compaction does not appear to be a serious problem on intensively prepared flatwoods sites (table 4). Surface soil bulk density of interbedded areas (Mascotte soil) of intensively prepared 1-year-old Bradford Forest plantations was 1.22 g/cm^3. Bulk densities of the undisturbed forest and minimal disturbance plantation were 1.07 and 1.09 g/cm^3, respectively. Intensive site preparation had less effect on bulk densities of the drier Stilson soils. Although small, these increases were larger than previously reported for intensively prepared flatwoods plantations. Schultz (1976) and Burger (1979) failed to detect any differences among site preparation treatments of various intensities.

2/ Comparisons for nonbedded areas.

Table 3--Distribution of nutrients in the forest floor of undisturbed flatwoods forests and of 1-year-old P. elliottii plantations

Treatment	Weight	N	P	K	Ca	Mg
	t/ha	(kg/ha)				
Undisturbed forest	36[2]	271	10	9	96	20
Minimal site preparation	36	184	8	7	95	18
Intensive site preparation	5	19	1	1	8	2
Treatment effect[3]	**	**	**	**	**	**

1/ Source: Morris (1981)
2/ All values are area weighted by soil type
3/ Indicates significant differences between at least two means (**, a = .01)

Table 4--Surface soil bulk density in 1-year-old Pinus elliottii plantations

Treatment	Soil type: Mascotte	Soil type: Stilson
	g/cm^3	
Undisturbed forest	1.07	1.18
Minimal site preparation	1.09	1.24
Intensive site preparation	1.22	1.27

Neither of the soils was sufficiently compacted by intensive site preparation to restrict growth. The difference in relative compaction between the wetter Mascotte and drier Stilson soils at the Bradford Forest suggests that compaction could be a problem in wet areas of the flatwoods or during wet periods. Compaction of yarding areas or heavily used skid trails was not specifically monitored in any of these studies. Although on a total-area basis compaction was not large, compaction of skid trails and yarding areas may have been severe enough to reduce growth in these areas.

Soil moisture.--It is well known that decreased transpiration following canopy removal results in an increase in overall soil water storage and a rise in the water table. On flatwoods sites, water table rises of up to 60cm occurred on intensively prepared sites during the summer following site preparation (Burger 1979, Pritchett and Wells 1978). These water table rises were not always reflected in increases of surface soil moisture. In fact, the surface soil of the intensively prepared Bradford Forest site was drier during the first growing season than either the minimally prepared site or unharvested forest (fig. 1). Apparently, rapid evaporation from the exposed mineral surface dried out the surface soil faster than upward movement from the water table (which was deep because of dry conditions) could replace it. In minimal disturbance plantations, the mulching effect of the residual-slash and forest floor was more effective in conserving surface soil moisture than the vegetation was at exhausting it. As a result of these differences, moisture-depletion profiles during precipitation-free periods were different for the two plantations (fig. 2).

Increased moisture availability through control of competing vegetation is one of the principal benefits ascribed to intensive site preparation. These data do not indicate large differences in total soil water content of the two plantations during the first growing season. The more pronounced wet and dry cycles that occurred near the surface of intensively prepared 1-year-old plantations were ephemeral and would not directly influence long-term site productivity.

Soil temperature.--Surface soil temperatures increased significantly following harvest and site preparation. Maximum temperatures in the intensively prepared Bradford Forest site often exceeded 55°C at 0.2 cm depth both in beds and interbed areas on cloudless days during the first growing season. Maximum temperatures beneath the residual forest floor of the minimally prepared plantation were 5°C to 10°C lower during the same

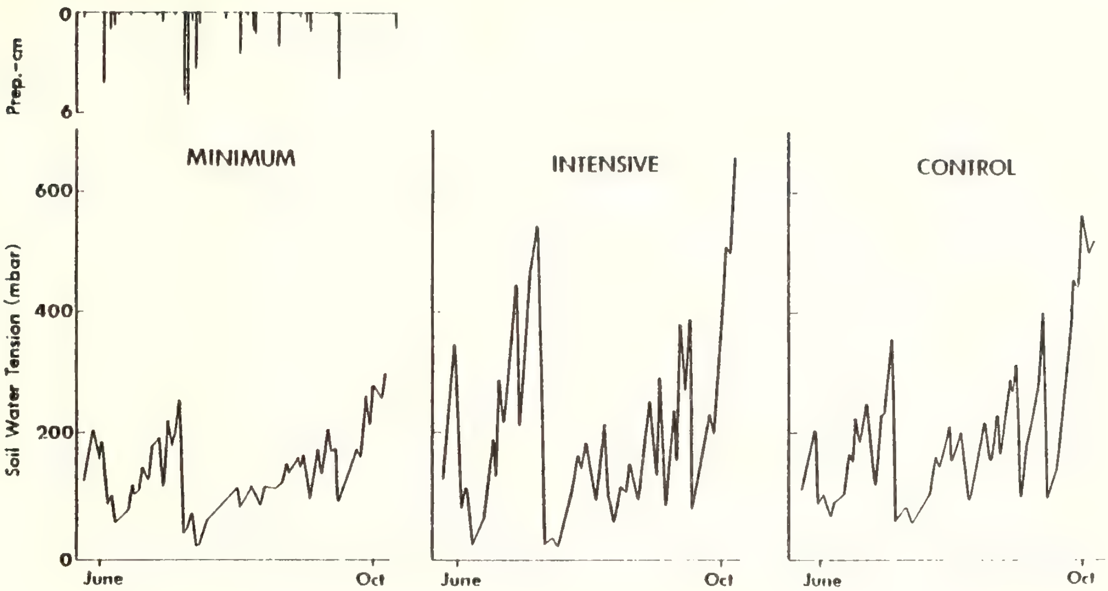

Figure 1.--Soil water tensions (total) at 5-cm depth during the first growing season in minimal-disturbance and intensively site-prepared P. elliottii plantations and in an undisturbed flatwoods forest (Source: Morris 1981).

periods. Temperatures at 10-cm depths were lower and differences among treatments were not as great. Temperatures at this depth reached 32°C in intensively prepared plantations compared to 28°C in the minimally prepared site and 24°C in the undisturbed control (fig. 3).

Cortical cells can be killed when seedlings are exposed to temperatures above 57°C for as little as 30 minutes (Lorentz 1939). Temperatures at the surface of intensively prepared plantations were above 57°C and some direct seedling damage may have occurred in these sites. Although short-term, these temperature increases could indirectly affect long-term productivity by stimulating decomposition and nutrient mineralization during a period when little vegetation was available to immobilize nutrients.

Changes in Biological Activity

Warmer conditions, more pronounced wet and dry

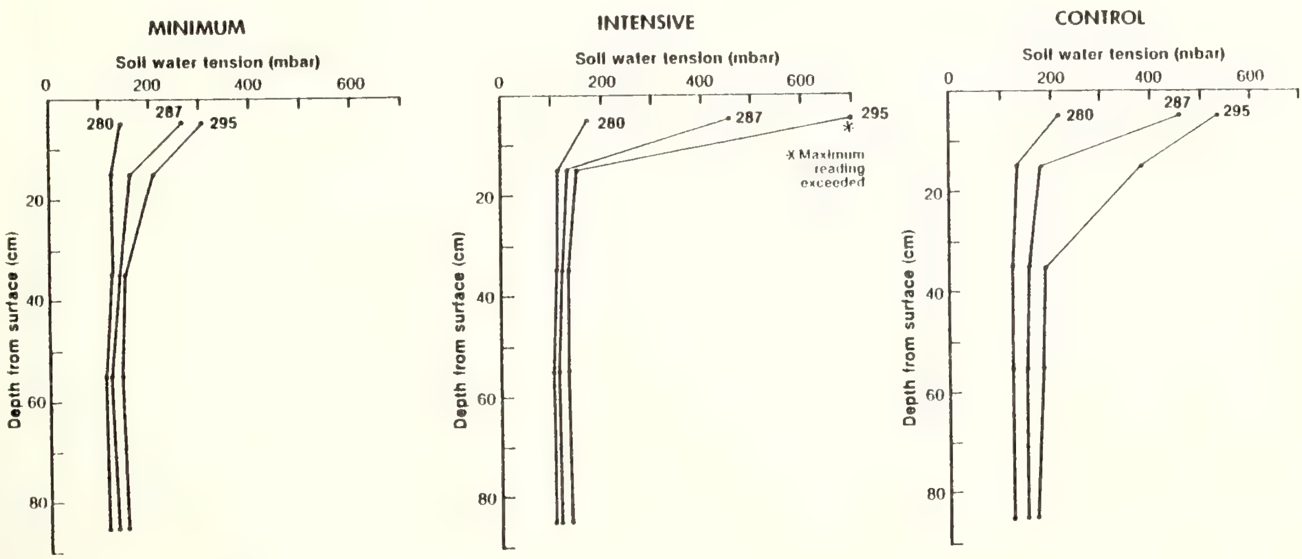

Figure 2.--Soil water tensions (total) during a precipitation-free period (Julian dates 280-295) of the first growing season in minimal disturbance and intensively site-prepared P. elliottii plantations and in an undisturbed flatwoods forest (Source: Morris 1981).

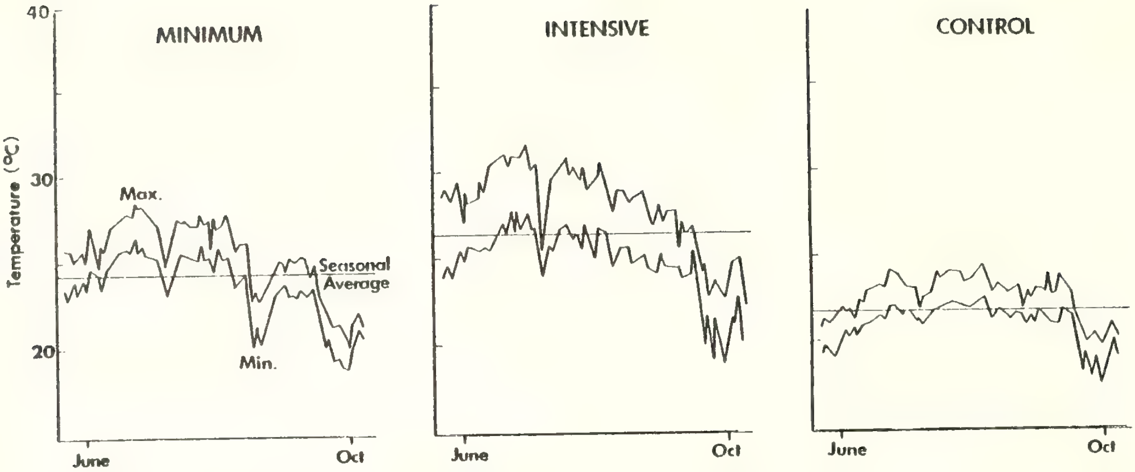

Figure 3.--Soil temperatures at 10-cm depth during the first growing season in minimal disturbance and intensively site-prepared P. elliottii plantations and in an undisturbed flatwoods forest (Source: Morris 1981).

cycles and mixing of the forest floor and mineral soil combined to promote greater biological activity in intensively prepared flatwoods sites. In the absence of large nutrient uptake by vegetation, this increased activity was reflected by increased soil solution nutrient concentrations. Soil solution inorganic nitrogen (NH_4-N and NO_3-N) concentrations of all three research sites were increased by intensive site preparation (Anonymous 1976, Burger 1979, Morris and Pritchett 1982). Peak NH_4-N and NO_3-N concentrations of about 2 ppm occurred during the first growing season, declining to baseline levels by the third growing season (figs. 4 and 5). Nitrogen flushing was less evident in the minimally prepared sites, but continued for longer periods at slightly elevated levels as residual slash and forest floor materials decomposed. Declines in mineralizable N contents in the surface soil followed similar patterns (table 5). Contents of mineralizable N were highest in intensively prepared plantations during the first growing season, but declined to below levels in the minimally disturbed plantation by the second growing season.

Table 5--Contents of mineralizable nitrogen in the surface 20 cm of young P. elliottii plantations and adjacent undisturbed forests

Plantation age (location)	Site preparation		
	Undisturbed control	Minimal disturbance	Intensive
	-------(kg/ha)-------		
One-year-old[1] (Bradford Forest)	52	70	88
Two-year-old[2] (Austin Cary Forest)	59	59	44

[1] Source: Morris (1981)
[2] Source: Burger (1979)

Tree growth is the best indicator of nutrient availability in flatwoods soils. An early release of nutrients plus control of competing vegetation often results in fast early growth for seedlings in intensively prepared sites. There are few long-term records of tree growth, however, to determine if this possible early advantage carries through the entire rotation. Some evidence indicates that it will not. The longest term growth data available in these studies are from the Owens-Illinois site where trees in the minimally prepared plantation averaged 4.4 m in height at 6 years--compared to 3.3 m in the intensively prepared plantations. Applications of NP fertilizers stimulated growth in the intensively prepared site to equal growth in the less intensively prepared site (Pritchett 1981) indicating the reduced growth may have been due to poor nutrition.

SUMMARY AND CONCLUSIONS

Field studies of the effects of harvest and site preparation on chemical, physical and biological properties of forest soils were conducted on three flatwoods forest sites in north central Florida. All three studies compared soil properties beneath an unharvested forest with properties of soils in P. elliottii plantations which had been regenerated following minimal disturbance (chop or chop and bed) and intensive (including windrowing) site preparation.

Forest floor weight and nutrient content were severely reduced following intensive site preparation. Most of this reduction resulted from displacement of organic materials from the planting surface into windrows during KG-blading. Although mineral soil was also pushed into windrows, this displacement was not large enough to reduce total N or extractable P, K, Ca and Mg concentrations on the surface soil.

Surface soils of intensively prepared plantations were characterized by higher temperatures and more pronounced wet and dry cycles than soils in minimal disturbance plantations. These altered

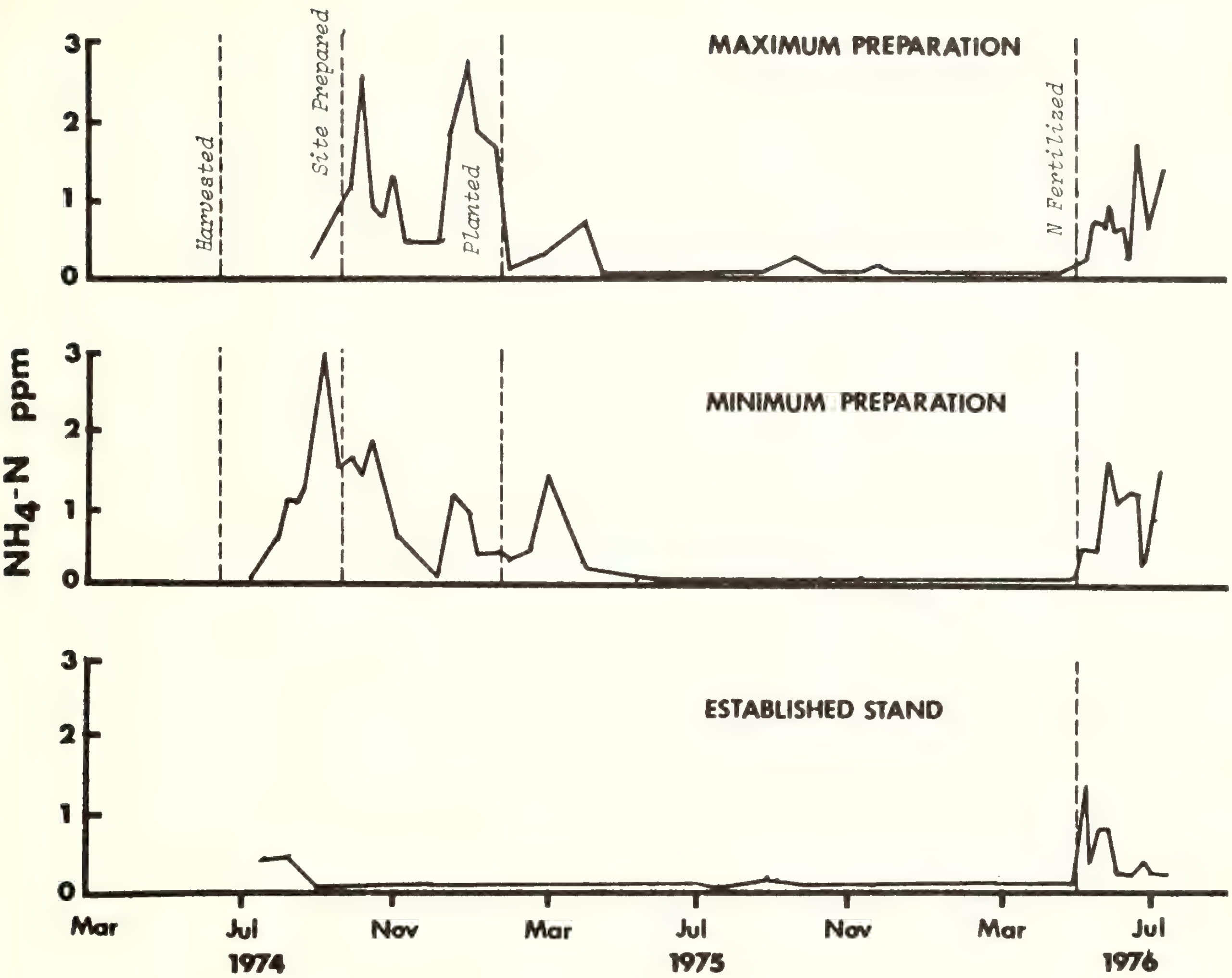

Figure 4.--Ammonium-N in soil solution at 30-cm depth in established stands and in harvested, site-prepared, and planted flatwoods forests (Source: Anonymous 1976).

physical properties can influence seedling development; however, they are ephemeral and would not directly affect long-term site productivity. Soil compaction, which can be severe enough to restrict root growth following harvest and site preparation on heavier textured soils, was not a serious problem on these sandy flatwoods sites.

Increased soil temperatures and more pronounced wet and dry cycles, which characterized the intensively prepared plantations, stimulated organic matter decomposition and N mineralization. This accelerated mineralization contributed to a reduction of mineralizable N contents in the surface soil of intensively site-prepared plantations. Ultimately, total soil N and overall soil fertility may decline as a result of forest floor removal during intensive site preparation.

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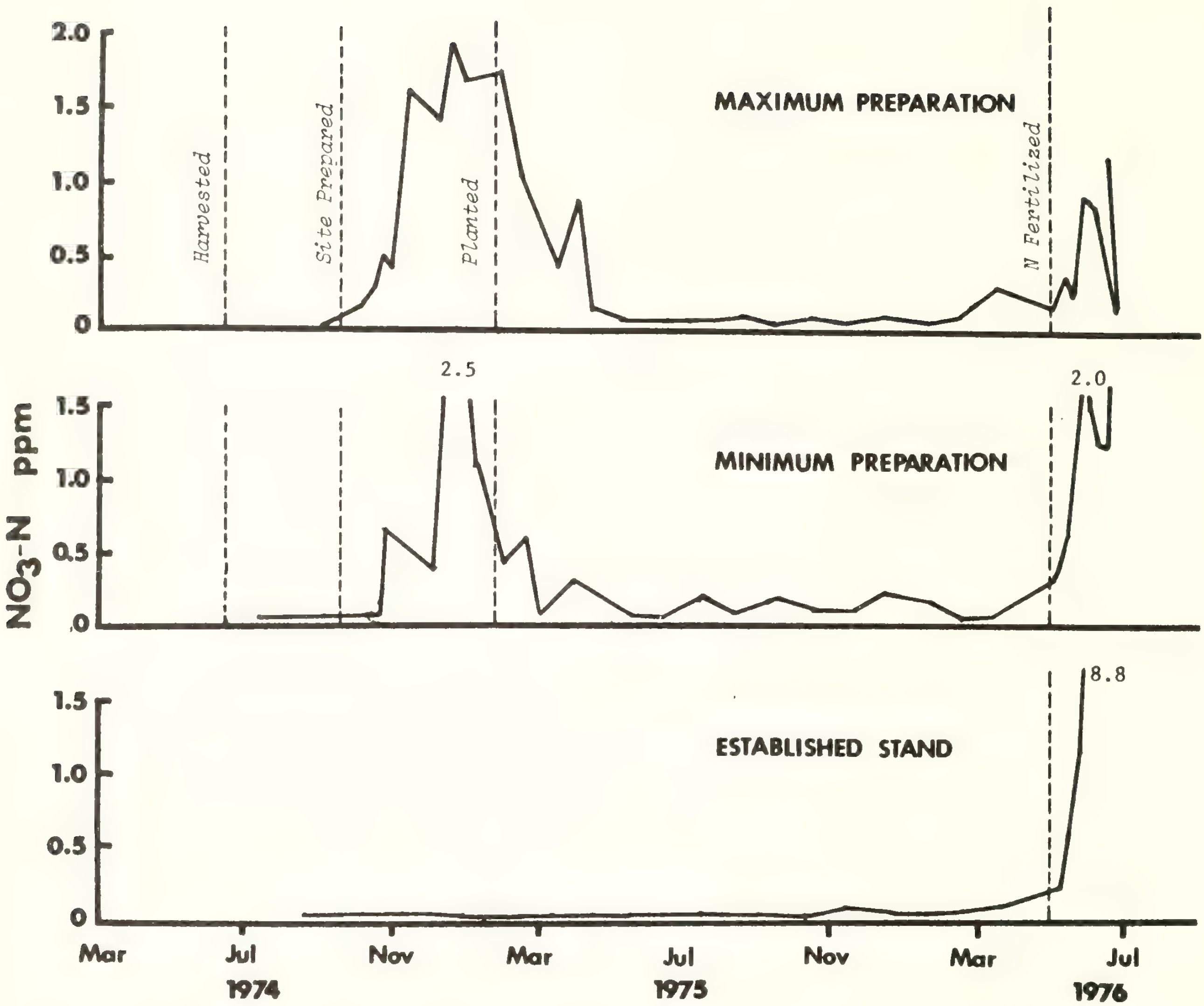

Figure 5.--Nitrate-N in soil solution at 30-cm depth in established stands and in harvested, site-prepared, and planted flatwoods forests (Source: Anonymous 1976).

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FOREST MANAGEMENT PRACTICES AND THE NUTRIENT STATUS OF A LOBLOLLY PINE PLANTATION

David H. Van Lear, Wayne T. Swank, James E. Douglass, and Jack B. Waide

ABSTRACT: Nutrient budgets for N, P, K, and Ca over a 41-year rotation were estimated for two loblolly pine (Pinus taeda L.) watersheds on poor sites in the upper Piedmont of South Carolina.

Whole-tree harvesting of above-stump biomass removed more than twice the N and P, and almost twice the K and Ca, as conventional harvest of boles only. Nutrient outputs exceeded inputs for P, K, and Ca on even the conventionally harvested watershed.

Harvesting and/or prescribed burning were the major causes of N and P loss from both watersheds, and stormflow and leaching were major sources of cation loss. Precipitation and N fixation were major sources of nutrient input to the ecosystems. Findings suggest that harvest of boles only on rotations of moderate length and leaving the forest floor and logging slash in place will help minimize adverse effects of clearcutting on the nutrient status, and thus the productivity, of these sites.

INTRODUCTION

Maintenance of site productivity in perpetuity is a basic tenet of forest resource stewardship. Forest soil scientists, ecologists, and silviculturists have recently become concerned that some intensive forest management practices may have an adverse impact on long-term productivity of the sites. Of special concern is the relatively new practice of whole-tree harvesting, which is becoming increasingly attractive to the wood-using industry as a means of increasing fiber production from a given land base (Boyle et al. 1973, Weetman and Webber 1972, White 1974). Others see whole-tree harvesting as a method of supplementing current and projected energy supplies in the United States (Office of Technology and Assessment 1979).

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Concern that intensive forestry will reduce forest site quality is more than academic. Reports from abroad have documented productivity declines in spruce in Saxony (Wiedemann 1923), and radiata pine in Australia (Keeves 1966) and New Zealand (Stone and Will 1965, Whyte 1973). Although actual declines in site productivity in response to management practices have not been documented in the United States, declines have been predicted on the basis of theoretical analyses, either from computer simulation (Swank and Waide 1980) or from nutrient budget analyses (Wells and Jorgensen 1975).

Effects of conventional and whole-tree (above-stump) harvesting on the nutrient status of two sites within a near-maturity loblolly pine plantation in the Piedmont of South Carolina are presented. Data collected from the last few years prior to harvest and the first 2 years following cutting were used to estimate nutrient inputs and outputs from each site over a rotation beginning with regeneration on freshly clearcut areas.

STUDY AREA

The study was conducted in an old field plantation of loblolly pine growing on the Clemson University Experimental Forest. Within the plantation, four small watersheds, ranging from 0.40 to 2.18 ha had been delineated in a previous study. Three of these watersheds were used in the present study: one served as the uncut

control, another was whole-tree harvested of all biomass above stump (whole tree), and the third was conventionally harvested.

The 41-year-old stand was harvested between mid-December 1979 to mid-January 1980. It had been thinned twice prior to harvest. Basal area of the pine overstory ranged from 15 to 22 m^2/ha. Growth rates were extremely low for the 5 years preceding harvest but are considered typical for older loblolly pine plantations in the highly eroded upper Piedmont. The soil was Pacolet fine sandy loam (Typic Hapludult, kaolinitic, thermic) and was well drained (slopes averaged 10-16 percent). Erosion has removed up to 75 percent of the A horizon of similar soils in the Piedmont (Byrd 1972). Perhaps due to past land use history, the whole-tree harvested watershed was not eroded as badly and supported about 33 percent more biomass than the other two watersheds. Precipitation averages 130 cm yearly and is generally well distributed.

Prior to harvest, three consecutive prescribed fires were conducted on the watersheds at yearly intervals to control understory hardwoods and prepare a seedbed. Strip head fires with ignition lines across the slope were used to accomplish the burning. Regeneration after harvest was accomplished naturally using clearcutting with seed in place (Lotti 1961).

METHODS

Biomass and nutrient content of trees in the plantation were estimated from regression equations developed from 16 trees growing in the stand (Van Lear et al. 1983). Data on biomass and nutrient content of each tree component were related to diameter at breast height (d.b.h.) in the model:

$$\text{Log}_{10}Y = a + b\ \log_{10}\text{d.b.h.}$$

where Y is the biomass or nutrient content of the tree component in kilograms and d.b.h. is expressed in centimeters. Diameters of all trees >7.6 cm were measured for each watershed.

Forest floor (O_1 and O_2 layers) and soil (0- to 8-, 15- to 23-, and 46- to 53-cm depths) were sampled quarterly after harvest from five 5- x 5-m locations on each watershed. The O_1 layer was collected within 1-m^2 quadrats, whereas the much thicker O_2 layer was sampled in an interior 0.09-m^2 quadrat. Because there is considerable mixing of soil with forest floor material, nutrient content of the forest floor is expressed on an ash-free basis.

Potential N fixation was measured on samples collected quarterly for 2 years from control and treatment watersheds using the acetylene reduction assay method (Hardy et al. 1968). Field-moist subsamples were transported to the laboratory in an ice chest. Approximately 100 g of soil or 10 g or O_1 and O_2 layers were transferred to 125-ml Erlenmeyer flasks fitted with serum stoppers; and 25 ml of C_2H_2 were injected into each flask. Three extra flasks of soil and litter were used for endogenous controls, and three empty flasks were used as acetylene controls. Samples were incubated for 24 hours at 18° C and then a 1-ml gas sample was extracted for analysis. Ethylene was determined by gas chromatography.

Dissolved nutrient output in stormflow was determined over a 3.7-yr preharvest period (1976-80) by sampling storm runoff from ephemeral stream channels with a 0.61-m-diameter Coshocton wheel set below 0.3-m H flumes. Stage height during storms was recorded on an analog-to-digital punch tape recorder. Flow sampled by the Coshocton wheel was diverted into plastic sample barrels from which subsamples were collected at weekly intervals for analysis. Concentration data were multiplied by stormflow quantities to calculate dissolved nutrient export.

Sediment loss of nutrients in stormflow was predicted by multiplying annual sediment export during the calibration period by the total nutrient concentration in soil samples from the 0-8-cm depth of each watershed. Nutrient loss in stormflow over the rotation is the sum of the dissolved nutrients and nutrients in sediment.

Loss to leaching was determined from nutrient concentrations in the soil solution collected at monthly intervals. Porous-cup tube lysimeters (suction set at 0.1 atm) were placed in the soil to a 50-cm depth at five locations per watershed. The volume of water moving beyond this depth was estimated by the difference in precipitation and potential evapotranspiration for the Clemson area. This difference was separated into stormflow and deep seepage components. Because of differences in channel morphology, only about 3 percent of precipitation was stormflow on watershed 64; 14 percent was stormflow on watershed 66 (Douglass and Van Lear 1983). Lysimeters were installed after harvest, so nutrient concentrations used for calculation of leaching losses within the latter part of the rotation were based on a 2-year record from the control, watershed 63.

During the early years of the rotation, elevated losses of nutrients occurred because of the lack of ground cover and the increase in both runoff and deep seepage. For this reason, stormflow and leaching losses of nutrients were calculated for the first 10 years of the rotation using concentration data from the first year after harvest and assuming a linear recovery rate to base-line condition; i.e., concentration prior to harvest.

Three low-intensity prescribed fires were applied to both watersheds prior to clearcutting to prepare the seedbed and to control understory hardwoods. Nutrient losses were calculated from measured weight reductions of the forest floor

during burning and nutrient concentrations of the O_1 layer following burning. McKee (1982) summarized prescribed burning effects on soil chemical properties and concluded that most of the cations and P in burned litter enters the mineral soil. Others have documented nutrient loss to ash convection (Clayton 1976, Kodama and Van Lear 1980, Lewis 1974). Therefore, we arbitrarily assumed 25 percent of the cations and P were lost in ash convection during the fires, and 75 percent was leached into the soil profile. Nutrients leached into the soil were considered to be part of the nutrient reserve. Nitrogen in the consumed litter was assumed lost to volatilization.

Input of nutrients in precipitation was collected in 1979 and 1980. Analyses were performed after rains produced a volume greater than 250 ml.

Mass balance differences (i.e., an index of potential weathering) were calculated as the difference between hydrologic outputs and precipitation inputs (Clayton 1979). Leaching and stormflow losses and precipitation inputs during the last years of the rotation were used to compute weathering input.

Water samples were analyzed for NO_3-N, NH_4-N, PO_4-P, Ca, and K on a Technicon Autoanalyzer and atomic absorption spectrophotometer. Total N in water, plant, and soil samples was measured by Kjeldahl analysis, and total P in plant and soil samples by perchloric acid digestion. Total K and Ca in plant tissue were determined by perchloric acid digestion, and total cations in soil were obtained by lithium metaborate fusion (Suhr and Ingamells 1966). Exchangeable K and Ca and extractable PO_4-P in soils were measured in a 0.05N HCl + 0.025N H_2SO_4 extract.

RESULTS AND DISCUSSION

Nutrient Inputs

Nutrient inputs in bulk precipitation (includes both wet and dry deposition) in 1979 and 1980 averaged 6.2 $kg.ha.^{-1}yr^{-1}$ for N(NO_3^--N + NH_4^+-N), and 0.2, 1.6, and 2.8 $kg.ha.^{-1}yr^{-1}$ for P, K, and Ca, respectively. These figures are similar to precipitation input at Hubbard Brook, New Hampshire (Likens et al. 1977) and at Coweeta Hydrologic Laboratory, North Carolina (Swank and Douglass 1977). Total input from precipitation over the 41-year rotation was estimated to be 254, 8, 66, and 115 kg/ha for N, P, K, and Ca, respectively (table 1).

Table 1--Nutrient inputs in two loblolly pine watersheds (WS) over a 41-year rotation

	Whole-tree harvest (WS 64)				Conventional harvest (WS 66)			
	N	P	K	Ca	N	P	K	Ca
	- - - - ($kg.ha.^{-1}41yrs^{-1}$) - - - -							
Inputs								
Precipitation	254	8	66	115	254	8	66	115
N fixation	144	-	--	---	152	-	--	---
Weathering	---	0	12	12	---	0	8	16
Total input	398	8	78	127	406	8	74	131

A summary of potential N-fixation data from free living organisms for the three catchments over a 2-year period showed an annual rate for the control of 3.7 $kg.ha.^{-1}yr^{-1}$. Estimates for the harvested catchments indicated a depression in fixation with rates of 2.4 and 1.7 $kg.ha.^{-1}yr^{-1}$ for the commercial and whole-tree harvests, respectively. Fixation rate over the course of a year appeared to respond most closely to moisture conditions. On the harvested sites, moisture content of the litter and surface soil samples were lower than for the control site, particularly in the summer and fall periods.

For the calculation of input in table 1, we assumed that fixation rates exhibit a linear recovery to control rates over 5- and 7-year periods for commercial clearcut and whole-tree harvesting treatments, respectively. Nitrogen accretion from fixation is a major input over the rotation and accounts for about 37 percent of the total input of N.

Input from weathering, as indexed by mass balance differences, ranged between 0.2 and 0.4 $kg.ha.^{-1}yr^{-1}$ for K and Ca on the two harvested watersheds. These rates are within the estimated weathering rates for K and Ca in other Piedmont studies (Cleaves et al. 1970, Cleaves et al. 1974). Inputs of P in precipitation exceeded losses to leaching and stormflow, so weathering input is shown as 0. Piedmont soils, such as the extremely old and highly weathered Pacolet series, would be expected to have low rates of nutrient release from parent material and primary minerals. Diffraction analysis of soil samples from harvested watersheds indicates that plagioclase feldspar and weathered mica are the primary sources of Ca and K, respectively.[1/] During short rotations of 20 years or so, nutrient loss in stormflow and leaching plus the rapid accumulation of nutrients in biomass and forest floor materials, may be too large to be compensated by weathering, as suggested by data from Wells and Jorgensen (1975). Using the mass balance equation in short rotations would predict unrealistically high rates of nutrient release in weathering.

[1/] Personal communication, Steven C. Hodges, soil chemist, Clemson University, Clemson SC.

Nutrient Outputs

Nutrient outputs, or removals, from the site are accelerated by whole-tree harvesting (table 2). Whole-tree harvest removed more than twice as much N and P as did conventional harvest, and almost twice the K and Ca. The relatively nutrient-rich portions of the tree (i.e., foliage, branches, and upper stem) are removed in whole-tree harvest, whereas conventional harvest took only the bole to a 15-cm top, which has a lower nutrient concentration. Comparison of nutrient removal between the two harvested watersheds must be tempered by the fact that, at harvest, watershed 64 contained about 133 t/ha above-stump biomass whereas watershed 66 had 100 t/ha. Nevertheless, if both watersheds had equal biomass, the magnitude of nutrient loss between the two harvest methods would still be dramatic.

Table 2--Nutrient outputs from two loblolly pine watersheds (WS) over a 41-year rotation

	Whole-tree harvest (WS 64)				Conventional harvest (WS 66)			
	N	P	K	Ca	N	P	K	Ca
	- - - - - ($kg.ha.^{-1}41yrs^{-1}$) - - - -							
Outputs								
Final harvest	151	13	68	134	63	5	36	70
Burning	160	1	4	15	94	1	4	10
Thinning (stems only)	16	1	9	18	16	1	9	18
Stormflow	11	1	17	18	33	1	97	68
Leaching	27	2	72	175	15	2	49	125
Total output	365	18	170	360	221	10	195	291

Forest-floor weight losses averaged about 8 000 kg/ha for the two treatment watersheds for the first burn, 4 000 kg/ha for the second burn, and about 1 750 kg/ha for the third burn. Because watershed 64 contained more fuel, greater quantities of nutrients were lost from that site during the three burns. Nitrogen loss to volatilization during burning was a major avenue of nutrient output, accounting for 44 and 43 percent of total output on watersheds 64 and 66, respectively. Others have reported large losses of volatile N during fire (Allen 1964, DeBell and Ralston 1970). Some of the N loss may be offset by an increased rate of N fixation from legumes, which were prevalent on burned and harvested watersheds, but symbiotic N fixation was not measured. Loss of cations and P to ash convection were estimated to be relatively small from these cool prescribed fires. If burning had been accomplished after logging, the convection loss of nutrients would have been much greater. In addition, most of the N in the forest floor and logging slash would have been volatilized. Burning, as used in this study, caused no significant losses of nutrients in stormflow (Douglass and Van Lear 1983).

Thinnings, which removed stems only, accounted for less than 10 percent of total output of N, P, K, and Ca (table 2). Thinnings, where branches and foliage are left on site, are a conservative method of harvest in regard to nutrients. In addition, the quantity of nutrients removed at final harvest is reduced in thinned stands.

Stormflow was about 3 and 14 percent of total precipitation for watersheds 64 and 66, respectively. These differences are due primarily to the effect of channel morphology; i.e., watershed 66 had a long, deeply incised channel that was highly responsive to precipitation events, and the channel in watershed 64 was relatively short, shallow, and less responsive. Nutrient loss to stormflow was therefore much greater from watershed 66 (table 2). Conversely, leaching loss was less from watershed 66 than from watershed 64.

The large quantity of nutrients lost to stormflow in a rotation is often overlooked. Ephemeral stream channels (i.e., gullies) that are relatively long and deeply incised carry away relatively large quantities of nutrients even after they are stabilized by a deep cover of pine needles. For certain cations (e.g., K from watershed 66) this may be the major mechanism of nutrient output.

Leaching losses were calculated from nutrient concentrations in lysimeters and estimated volumes of soil moisture passing beyond the porous cup (table 2). Although the porous cup was inserted to a depth of only 46-50 cm, probably 90 percent of the feeder roots of loblolly pine are above this depth on eroded Piedmont sites. Therefore, the majority of nutrients leaching beyond this depth presumably percolate to groundwater or move laterally downslope beyond the watershed boundaries. We used this hypothesis even though it needs field verification. In contrast to stormflow losses, leaching losses of nutrients, except for P, were much greater on watershed 64 than on watershed 66. A much greater proportion of precipitation percolated deeply on watershed 64, because stormflow was only 3 percent of precipitation. The site specificity of nutrient cycling processes is dramatically indicated in the comparison of stormflow and leaching losses between these two adjacent watersheds.

Input of N exceeded output over the length of the rotation for both the conventionally and whole-tree harvested watersheds (table 3). However, N input exceeded output on the whole-tree harvested watershed by only 9 percent whereas inputs exceeded outputs by 84 percent on the conventionally harvested watershed. We should point out that potential N loss by denitrification was not measured in this study, although losses to this process are thought to be low on these well-drained sites. Also, symbiotic N fixation was not measured but could have contributed significant amounts of N input since leguminous species were observed on both sites. Outputs of P exceeded inputs for both watersheds, but the

deficit was five times as great on the whole-tree harvested watershed. This difference in net P balance can be attributed to harvesting method alone, because burning, thinning, and hydrologic losses were the same for both watersheds. Outputs of K and Ca exceeded inputs on both watersheds.

Table 3--Net balance of nutrients in two loblolly pine watersheds over a 41-year rotation

Watershed number	Item	Nutrient N	P	K	Ca
		- ($kg.ha.^{-1}41\ yrs^{-1}$) -			
64 (whole-tree harvest)	Input	398	8	78	127
	Output	365	18	170	360
	Net balance	+33	-10	-92	-233
66 (conventional harvest)	Input	406	8	74	131
	Output	221	10	195	291
	Net balance	+185	-2	-121	-160

Results of this nutrient budget analysis indicate that inputs of certain nutrients (e.g., P, K, and Ca) are not keeping pace with outputs on these poor Piedmont sites even under conventional harvesting systems. Under whole-tree harvesting, nutrient drain is greater (although this is not clearly shown for K because of the greater hydrologic loss of this element on watershed 66).

Nutrient Reserves

Nutrients in the mineral soil are considered reserves because mineral soil supplies a small proportion of the stand's annual requirements, especially after the forest floor reaches an equilibrium mass. Early in the rotation, nutrients supplied by the soil may be much more important. Total N in the mineral soil was about 10 percent higher on watershed 64 (table 4), which supported 33 percent more biomass. The striking difference, however, is that watershed 64 contained more than twice the total calcium of watershed 66. Whether high concentrations and quantities of Ca in watershed 64 are due to past land-use history or to geologic differences is not known.

The forest floor is a ready source of nutrients for regeneration, because of accelerated decomposition following clearcutting (Bormann et al. 1968). Nitrogen was the most abundant nutrient in the forest floor just prior to harvest; i.e., 176 and 132 kg/ha for watersheds 64 and 66, respectively (table 5). Phosphorus was the least abundant of the elements analyzed in the forest floor with 12 kg/ha for watershed 66 and 17 kg/ha for watershed 64.

Table 4--Total and extractable nutrient content in the mineral soil of two loblolly pine watersheds in the Piedmont of South Carolina

Depth	N	P	K	Ca
	Whole-tree harvest (WS 64)			
	- - - - - - (kg/ha) - - - - - -			
Total (0-60 cm)	2 336	520	17 134	20 690
Extractable[1/]				
(0-8 cm)	--	10.7	29	166
(9-34 cm)	--	4.6	102	639
(35-60 cm)	--	1.4	82	527
		16.7	213	1 332
	Conventional harvest (WS 66)			
Total (0-60 cm)	2 118	748	13 526	9 581
Extractable[1/]				
(0-8 cm)	--	7.6	34	128
(15-23 cm)	--	3.7	41	190
(46-53 cm)	--	1.3	34	183
		12.6	109	501

[1/]Extractable P expressed as PO_4-P

Table 5--Nutrient reserves from organic residues

Source	Whole-tree harvest (WS 64) N	P	K	Ca	Conventional harvest (WS 66) N	P	K	Ca
	- - - - - ($kg.ha.^{-1}41\ yrs^{-1}$) - - - -							
Forest floor decomposition	176	17	22	164	132	12	17	102
Logging residues	-	-	-	-	50	5	16	32
Thinning residues	13	2	5	9	13	2	5	9
Stumps and roots	39	7	26	39	29	5	20	29
Total	228	26	53	212	224	24	58	172

Foliage on logging slash releases its nutrients rather quickly, but woody logging debris does not contribute nutrients until much later when the C:element ratio becomes more favorable for net mineralization and uptake (Covington 1981). The amount of nutrients in logging debris on watershed 66 appears low compared to data of Wells and Jorgensen (1975). Differences are attributed to site, stand, and management factors. This site was an eroded upland of poor to average site

quality, whereas the site studied by Wells and Jorgensen was a high quality old-field site. Their stand was a vigorous 16-year-old plantation nearing a peak nutrient-accumulation rate, and our 41-year-old plantation was near biological maturity. In this study whole watersheds, which contained a logging road and old skid trails, rather than small plots were used. Another important feature contributing to difference in biomass of the two studies is that the 41-year-old plantation had been thinned twice.

Management records indicate that about 21 tons/ha of stem biomass was removed in light low thinnings before the study began with about 14 percent of total tree biomass in branch and foliage remaining on site following thinning. Estimated nutrient reserves from thinning residues ranged from 2 kg/ha for P to 13 kg/ha for N.

Nutrient reserves in root systems were not measured but were estimated from published relationships between nutrient content of tops and roots of loblolly pine in the Piedmont of North Carolina (Wells and Jorgensen 1975). While fine roots certainly decompose rapidly, larger roots decompose rather slowly. Because of the high C:element ratio of these large roots, decomposition may immobilize significant quantities of N and P (Ralston 1978). As the C:element ratio decreases during subsequent decay, elements are released for uptake by the plant. In this respect, nutrient dynamics in large decomposing roots and woody logging debris are similar; i.e., both provide N and P for stand nutrition after the regeneration period.

At first glance, nutrient removal in harvest, erosion, burning, or leaching seems insignificant when compared to nutrient reserves in the mineral soil and those available from decomposition of organic reserves. It is the rate of nutrient availability that is important to productivity; however, nearly all the N and a large portion of the P in southern forest soils are located in a rather stable humus (mineral soil organic complex) fraction that has developed over centuries (Pritchett and Wells 1978). Mineralization of the soil humus fraction and the larger forms of the organic residues are slow and likely would not be adequate to satisfy nutritional demands of a rapidly growing new stand. Rates of N mineralization as affected by harvest of these sites are currently under study and will be reported later. Nutrient inputs from weathering indices are low for this soil and deficits of P, K, and Ca may contribute to potential declines in site productivity, especially where whole-tree harvesting is practiced on eroded Piedmont sites. The negative net balance of P, K, and Ca (table 3) is a significant portion of the extractable quantities of these nutrients (table 4).

SUMMARY AND CONCLUSIONS

Management practices have a major effect on the nutrient status of loblolly pine ecosystems. Assuming stands of equal biomass, whole-tree harvesting removes about 45-50 percent more N and P and 37 percent more K and Ca than would conventional harvest. Frequent prescribed fires, even those of low intensity, can be a major source of N loss through volatilization. Conversely, thinning removes stem biomass of relatively low nutrient content and leaves the nutrient-rich foliage and branches to decompose on the site.

Topography and hydrology affect nutrient flux. Adjacent watersheds with similar vegetation and overall slope but differing in channel depth and length exhibit markedly different nutrient output for some elements. Potential weathering rates are low for these weathered kaolinitic soils. Nutrient release from weathering appears to be unable to replace those removed in harvesting, especially whole-tree harvesting.

Results indicated that even conventional harvesting had an adverse impact on P, K, and Ca status of the ecosystem. Output of these nutrients exceeded inputs on both harvested watersheds. This net drain represented a significant percentage of the extractable nutrient pool. Whole-tree harvesting increased the net deficit of P and Ca. In addition, N inputs exceeded outputs by only 9 percent on the whole-tree harvested watershed. When nutrient losses exceed nutrient gains to the ecosystem, reserves from the mineral soil and organic sources will have to compensate for the deficit to maintain current productivity levels. The question is for how many rotations can this reserve be taxed without adversely affecting site productivity.

The length of the rotation is important in evaluating nutrient status. The shorter the rotation, the greater the rate of nutrient loss to stormflow and leaching. In addition, the rate of nutrient accumulation in biomass is greatest during the early phase of the rotation, and therefore rate of nutrient removal at harvest is greater. Finally, a short rotation does not provide adequate time for nutrient accumulations through precipitation, weathering, and N fixation. For these reasons, nutrient drain is faster for short rotations.

Whole-tree harvesting and frequent prescribed burning can markedly accelerate nutrient losses from loblolly pine ecosystems. On these eroded, highly weathered Piedmont soils, harvest of boles only on relatively long rotations while leaving logging slash and forest floor in place will help reduce the impact of harvesting operations on site nutrient status.

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FOREST MANAGEMENT EFFECTS ON SOIL NITROGEN IN *EUCALYPTUS PAUCIFLORA* AND *PINUS RADIATA* STANDS IN THE AUSTRALIAN CAPITAL TERRITORY, AUSTRALIA

Robert L. Edmonds and John G. McColl

ABSTRACT: The influence of clearcutting *Pinus radiata* plantations and prescribed burning of *Eucalyptus pauciflora* forests in the Australian Capital Territory on soil nitrogen mineralization and nitrification were determined. Nitrogen mineralization rates were low (<3ppm/mo) in both treatments, and were only slightly elevated over control rates. Nitrification was insignificant. Soil nitrate concentrations in the 0-7 cm depth were less than 100 ppb in both pine and eucalypt site soils.

INTRODUCTION

Forest management practices such as clearcutting and the use of prescribed burning may influence tree growth by affecting soil nitrogen availability. The conversion of native eucalypt forest to radiata pine (*Pinus radiata* D. Don) plantations results in reduced soil organic matter and nitrogen levels (Hamilton 1965). Such sites may then be nitrogen deficient in the next rotation, particularly if prescribed burning is used for slash reduction. Tree growth is very poor on sites treated in this manner in the Australian Capital Territory (A.C.T.) (I. Gordon, A.C.T. Forests, Canberra, personal communication).

There is also evidence in South Australia of a decline in productivity of second rotation *Pinus radiata* plantations following clearcutting of the first rotation crop and slash burning (Keeves 1966). Many of these soils had formerly been used for agriculture. Considerable research has been conducted to determine the causes of this decline (Flinn *et al*. 1979 and 1980, Florence 1967, Florence and Lamb 1975, Hopmans *et al*. 1980, Squire *et al*. 1979), and many factors have been implicated, including soil N availability.

Prescribed fire is not only used for slash reduction in plantations, but is also used to reduce fuel loads in native eucalypt forests to protect against wildfires. It is used commonly in the subalpine (*Eucalyptus pauciflora* Sieb. ex Spreng) forests in the watersheds surrounding Canberra in the A.C.T. Concern over the use of this practice has been raised because frequent use of fire may reduce organic matter and nitrogen on such sites. It has been suggested that these losses may result in depauperate forests and lowered water quality.

This study was undertaken to determine the influence on soil nitrogen mineralization and nitrification rates of (1) cutting first-rotation radiata pine stands and (2) using prescribed fire in *Eucalyptus pauciflora* forests.

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STUDY AREAS

Pine Site

This site was located in Uriarra Forest in the Brindabella Range approximately 24 km east of Canberra, A.C.T. The yellow soils on the site are derived from volcanic Silurian parent material. Three stands were selected: a 45-year-old first-rotation pine stand; a naturally regenerated 5-year-old pine stand; and a clearcutting which resulted from windthrow in June 1981. The clearcutting was planted in winter 1981 with radiata pine seedlings. Elevation of the site was 671 m, aspect was N. 60 E. and the slope was 7 degrees. Tree heights averaged 32, 6.4 and 1.2 m, in the 45-year-old, 5-year-old, and clearcut areas, respectively. Climate in the area is characterized by cold winters and warm summers. Mean annual rainfall is about 1,000 mm with no seasonal pattern. Hot, dry periods of 6-8 weeks are common during December-February. Winter snow is common, but the soil rarely freezes.

Eucalyptus Site

This site was also located in the Brindabella Range approximately 50 km southeast of Canberra on a red earth-Kraznozem soil derived from parent material of highly weathered Ordovician sediments.

Elevation was 1,250 m. Dominant overstory vegetation was Eucalyptus pauciflora while the understory was dominated by Daviesia mimosoides, a nitrogen-fixing shrub. Climate is similar to the pine site but the rainfall is slightly higher (1,150 mm mean annual). Temperatures are slightly cooler and snow persists longer.

Three burning treatments were involved: (1) a light understory burn in December 1981, (2) an area that had not been burned for 3 years, and (3) an area that had not been burned for 19 years.

METHODS AND MATERIALS

The method for determining nitrogen mineralization and nitrification rates was adapted from Rapp et al. (1979). Thick-walled steel tubes (5-cm inside diameter x 25-cm length) with beveled bottom edges were driven into the soil at the beginning of each 4-week incubation period. Twelve cores in each of the three pine stands and burning treatments were taken for the initial sampling, but this was reduced to 6 cores for subsequent samples. An additional 12 tubes were driven into the soil at the time of each baseline sampling, covered with a plastic top, and left for 4 weeks before removal.

To assess NH_4^+- and NO_3^--N concentrations tubes were transported to the laboratory and stored at 3°C until processed. Cores were removed from the tubes and divided into two horizons. The upper dark organic horizon averaged 0-7 cm, and the lower horizon had depths of 7-20 cm (pine site) and 7-22 cm (eucalypt site). After sieving through a 2-mm sieve the wet and dry weight of soil in each horizon was determined. Ten g of wet sieved soil were then placed in 50 ml of 2N KCl and shaken for 1 hour on a rotary shaker. The solution was then filtered through Whatman No. 42 filter paper and analyzed for NH_4^+-N using an autoanalyzer. Because of interference on the autoanalyzer, the KCl solution could not be used for NO_3^--N analysis. For this analysis an additional 10 g of soil was placed in 50 ml of deionized water and shaken for 1 hour. The pH of this solution was determined with a pH meter. It was then filtered as above with additional filtration through a 0.5-μm millipore filter, and analyzed for NO_3^--N on the autoanalyzer. The pine site was sampled monthly from November 1981 to May 1982, and the eucalypt site was sampled in December 1981 (immediately after the fire) and in January 1982. Concentrations were converted to kilograms per hectare. Total (Kjeldahl) nitrogen and organic matter (Walkley-Black) were determined in the two soil horizons from each treatment of each site.

RESULTS

Soil Nitrogen, Organic Matter and pH

In the eucalypt site nitrogen concentrations ranged from 0.24 to 0.37 percent; organic matter ranged from 7.1 to 10.0 percent (table 1). Ranges in the pine site were 0.05 to 0.14 percent for nitrogen and 0.8 to 4.2 percent for organic matter. In both horizons, nitrogen and organic matter concentrations were significantly higher ($p<0.01$) in the eucalypt site than in the pine site (table 1).

In the pine site concentration of nitrogen in the upper horizon was significantly higher than that in the lower horizon ($p<0.05$) only in the 5-year-old stand. Organic matter concentrations, however, were significantly higher ($p<0.01$) in the upper horizons in all three pine stands. There were no significant differences in either nitrogen or organic matter concentrations in the upper and lower horizons in the eucalypt site.

Soil pH was significantly higher ($p<0.01$) in the pine site (range 5.4 - 6.2) than in the eucalypt site (range 4.6 - 5.0) (table 1). Burning did not increase the pH in the upper horizon of the eucalypt site. In general there were no significant differences in soil pH between treatments with the exception of the lower horizon in the clearcut pine site, which was higher (pH 6.2, $p<0.01$) than that in the other pine stands.

Soil Ammonium and Nitrate Concentrations

Typical concentrations of NH_4^+- and NO_3^--N in the pine site for two sampling times (spring and summer) are shown in table 2 for the upper (0-7 cm) soil horizon. Ammonium concentrations generally were low with highest concentrations (1.5 ± 0.6 and 1.6 ± 0.8 ppm) occurring in the clearcut stand and lowest concentrations (0.8 ± 0.1 and 1.0 ± 0.3 ppm) in the 45-year-old stand. Concentrations of NH_4^+-N were not significantly different, however, between treatments or seasons.

Table 1--Total nitrogen, organic matter (OM), and pH (± standard deviations) in the upper and lower horizons of soils in a Eucalyptus pauciflora stand with different burning treatments and Pinus radiata stands of different ages in the Australian Capital Territory

	Depth (cm)					
	0-7			7-22		
	N	OM	pH	N	OM	pH
	----Percent----			----Percent----		
Eucalypt						
Fresh burn	0.37(0.06)	10.0(1.0)	4.6(0.3)	0.24(0.05)	7.2(1.5)	4.7(0.1)
3 years	0.33(0.05)	8.9(2.3)	4.7(0.2)	0.24(0.10)	7.1(2.6)	5.0(0.2)
19 years	0.30(0.05)	9.1(1.6)	4.7(0.2)	0.25(0.05)	8.8(2.0)	4.9(0.2)
Pine						
Clearcut	0.13(0.04)	4.2(1.6)	5.8(0.5)	0.06(0.02)	1.3(0.5)	6.2(0.2)
5-year-old	0.14(0.02)	4.1(1.1)	5.5(0.6)	0.05(0.01)	1.3(0.3)	5.4(0.3)
45-year-old	0.09(0.01)	3.7(0.6)	5.8(0.3)	0.06(0.01)	0.8(0.2)	5.6(0.3)

Nitrate concentrations were very low (less than 100 ppb) and were not higher in the clearcut in comparison to the other treatments. Significantly, lower concentrations ($p<0.01$) occurred in summer than spring (table 2).

Table 2--Soil ammonium and nitrate nitrogen concentrations (± standard deviations) in the 0 to 7-cm horizon on November 17, 1981, and February 15, 1982, in 45-year-old, 5-year-old and clearcut radiata pine stands in the Australian Capital Territory

Treatment	Date: Nov. 17, '81	Feb. 15, '82
	----NH_4^+-N(ppm)----	
45-year-old	1.0 (0.3)	0.8 (0.1)
5-year-old	1.2 (0.2)	0.9 (0.2)
Clearcut	1.6 (0.8)	1.5 (0.6)
	----NO_3^--N(ppb)----	
45-year-old	89 (34)	22 (6)
5-year-old	92 (21)	33 (13)
Clearcut	82 (36)	42 (19)

Table 3 shows concentrations of NH_4^+-and NO_3^--N in the eucalypt site in the upper soil horizon on December 12, 1981, immediately after the fire, and on January 5, 1982, 4 weeks after the fire. Ammonium concentrations ranged from 2.3 ± 0.4 to 3.6 ± 0.8 ppm in this period. Immediately after the fire, highest soil NH_4^+-N concentrations occurred in the freshly burned plot (3.6 ± 0.8 ppm) but this elevated concentration was not significantly different from concentrations in other treatments (table 3). It was significantly different ($p<0.01$), however, from that occurring in the same treatment 1 month later (table 3). Concentrations of nitrate were extremely low ranging from 28 ± 10 to 50 ± 67 ppb (table 3). There were no significant differences between treatments or seasons in NO_3^--N concentrations

Table 3--Soil ammonium and nitrate nitrogen concentrations (± standard deviations) in the 0 to 7-cm horizon on December 12, 1981, and January 5, 1982, in a Eucalyptus pauciflora stand which had been freshly burned, and not burned for 3 and 19 years, respectively in the Australian Capital Territory

Treatment	Date: Dec. 12, '81	Jan. 5, '82
	----NH_4^+-N(ppm)----	
Fresh burn	3.6 (0.8)	2.3 (0.4)
3-year burn	3.0 (0.7)	3.2 (0.6)
19-year burn	2.7 (0.4)	2.5 (0.5)
	----NO_3^--N(ppb)----	
Fresh burn	37 (11)	28 (10)
3-year burn	47 (13)	35 (11)
19-year burn	40 (8)	50 (67)

Nitrogen Mineralization Rates

Typical soil nitrogen mineralization rates for both sites are shown in table 4. The highest nitrogen mineralization rate in the pine site upper horizon occurred in the clearcut treatment (0.9 ± 1.6 ppm NH_4^+-N/mo) but because of high variability it was not significantly different from the lowest mineralization rate (0.4 ± 1.0 ppm NH_4^+-N/mo) which occurred in the 45-year-old stand. This is equivalent to 0.4 kgNH_4^+-N ha^{-1} mo^{-1} in the clearcut treatment. Only 0.2 kgNH_4^+-N ha^{-1} mo^{-1} was mineralized in the lower horizon for a total of 0.6 kgNH_4^+-N ha^{-1} mo^{-1} mineralized for the 0-20-cm layer in the clearcut.

Nitrogen mineralization rates were higher in the eucalypt than pine soil, particularly immediately after the fire (2.7 ± 7.4 ppm NH_4^+-N/mo, table 4).

Table 4--Nitrogen mineralization rates ($\pm$ standard deviations) in the 0 to 7-cm soil horizon in the pine site from January 18 to February 15, 1982, and the eucalypt site from December 12, 1981, to January 5, 1982, and January 5 to February 4, 1982

Treatment	NH_4^+-N(ppm)		Mineralization rate (ppm NH_4^+-N/mo)
	Pine site		
	Baseline Jan. 18	Final Feb. 15	
45-year-old	1.0 (0.3)	1.4 (1.0)	0.4 (1.0)
5-year-old	1.4 (0.4)	2.0 (0.7)	0.6 (0.6)
Clearcut	1.8 (0.9)	2.7 (1.3)	0.9 (1.6)
	Eucalyptus site		
	Dec. 12	Jan. 5	
Fresh burn	3.6 (0.8)	6.3 (7.2)	2.7 (7.4)
3-year burn	3.0 (0.7)	2.6 (0.8)	-0.4 (1.1)
19-year burn	2.7 (0.4)	3.3 (0.7)	0.6 (0.9)
	Jan. 5	Feb. 4	
Fresh burn	2.3 (0.4)	3.5 (1.5)	1.2 (1.2)
3-year burn	3.2 (0.6)	3.6 (1.6)	0.4 (1.1)
19-year burn	2.5 (0.5)	4.3 (2.4)	1.8 (1.9)

Because of high variability, this rate was not significantly different from that occurring 1 month after the fire (1.2 $\pm$ 1.2 ppm NH_4^+-N/mo), and was similar to mineralization rates in plots unburned for 3 and 19 years. The nitrogen mineralization rate immediately after the fire was 1.2 kgNH_4^+-N ha^{-1} mo^{-1} for the upper horizon and 0.2 kg NH_4^+-N ha^{-1} mo^{-1} for the lower horizon resulting in a total of 1.4 kgNH_4^+-N ha^{-1} mo^{-1} for the 0 to 22-cm layer.

Nitrification Rates

Very little nitrate was produced after incubation in any of the treatments at the two sites. Production of nitrate ranged from 20-50 ppb per mo. at the pine site and 0-20 ppb per mo. at the eucalypt site. There was no clear relationship between burning or clearcutting and increased soil nitrification rates.

DISCUSSION

Total soil nitrogen and organic matter concentrations in the eucalypt site were significantly higher than those in the pine site and soil pH was significantly lower. Concentrations of nitrogen were higher in the upper horizons of the pine site than the lower horizons, but were only significantly different in the 5-year-old stand. There were no significant differences in nitrogen concentrations between horizons in the eucalypt site but the upper horizons were higher. Organic matter concentrations decreased significantly with depth in the pine site but not in the eucalypt site. Low nitrogen and organic matter concentrations in the pine site probably reflect conversion of the original eucalypt forest on the site to *Pinus radiata*. Similar trends were found by Hamilton (1965) in the same area. It should be pointed out, however, that a direct comparison of pine versus eucalypt sites cannot be made with our data because the eucalypt site was at a higher altitude than the pine site, and the original vegetation would not have been *E. pauciflora*.

The trends in total soil nitrogen concentrations in the eucalypt and pine sites are also reflected in the concentration of soil NH_4^+-N. Ammonium concentrations were two to three times higher in the eucalypt site soil (table 3) than in the pine site soil (table 2). Nitrogen mineralization rates were higher, but not significantly, in the eucalypt site soil than the pine site soil (table 4).

Pine management practices influence soil nitrogen mineralization rates. The highest rate of soil nitrogen mineralization occurred in the clearcut with the next highest rate in the 5-year-old stand and the lowest rate in the 45-year-old stand. Because of high variability, however, no significant differences between treatments occurred.

In the eucalypt site the highest rate of mineralization in the 0 to 7-cm soil horizon occurred in the month immediately after the fire (table 4), but because of high variability, differences between treatments were not significant. The influence of the fire appeared to last only for the first month after the fire. Observed fire effects may have been greater had sampling been carried out at a finer scale; e.g., 0 to 1 cm.

On a kilogram per hectare basis it is apparent that the nitrogen mineralization rates observed in both the pine and eucalypt stands are very low and may not be adequate in the pine site to meet uptake requirements of young trees. Nitrogen losses occurring after fire in native eucalypt

forests can be replaced by nitrogen-fixing legume species such as Daviesia mimosoides (McColl and Edmonds 1983). No native nitrogen-fixing plants grow in pine plantations, and nitrogen lost as a result of removing eucalypt forests and planting radiata pine can only be replaced by fertilization.

The process of nitrification has received considerable attention particularly with respect to losses of nitrogen as a result of clearcutting and exposure to fire. Soils under Pinus radiata and Eucalyptus pauciflora produced very little nitrate after clearcutting and fire treatment, respectively. Nitrate concentrations were very low even after incubation for 1 month.

Factors influencing nitrification in forest ecosystems include (1) substrate (NH_4^+) levels, (2) environment--temperature and moisture, (3) low pH, (4) lack of nitrifiers, and (5) chemical inhibition of nitrifiers. Nitrification in our study may have been affected by low pH (4.6 - 5.0 in eucalyptus, 5.4 - 6.2 in pine) and low concentrations of NH_4^+. Fertilization of the clearcut pine site with NH_4Cl_2 (at a rate of 400 kg N/ha), however, did not cause an increase in the rate of nitrification. More studies are needed to determine the specific factors controlling nitrification in these ecosystems.

The forest management practices discussed here will not dramatically increase the rate of nitrification in pine and eucalypt ecosystems that have low soil N levels. However, not all Australian forest ecosystems have low rates of nitrification. Rainforest ecosystems in Queensland have high nitrification rates (Lamb 1980) and management of these forests may increase nitrogen losses.

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ENVIRONMENTAL IMPACTS OF INTENSIVE SILVICULTURE IN FLORIDA

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ABSTRACT: Five operational-sized watersheds were constructed in Florida's poorly drained flatwoods landscape. A 12-month calibration period was followed by four treatments, including a range of biomass removals and levels of intensity of site preparation for forest regeneration, plus a control.

Biomass and nutrient removals, precipitation input, and runoff output were monitored for several years. The data show a rapid return of runoff increases and water quality degradation to baseline levels. Biomass nutrient exports represent the major pathway of nutrient losses. Conventional pulpwood harvesting did not significantly affect nutrient balances. Whole-tree harvesting and total-tree harvesting (including stumps) led to significant nutrient losses.

INTRODUCTION

Intensive forest management in the southeastern United States developed rapidly during the last few decades. Harvest and site preparation techniques plus genetically improved planting stock have greatly increased demands on the productive potential of forest soils.

The lower coastal plain of northern Florida is dominated by poorly drained pine flatwoods interspersed with cypress swamps. The sandy and acid-leached soils are low in nutrients and contain little weatherable minerals. Soil organic matter provides the main supply of available nutrients for trees (Morris and Pritchett 1982).

Increased forest biomass production and harvesting by modern silvicultural practices, which approach agricultural levels of management intensity, remove major plant nutrients and, more importantly, deplete soil humus. Lower nutrient retention capacity by the soil results in accelerated leaching losses (Leaf 1979).

Concern about forest soil degradation with attendant downstream water pollution has resulted in several complementary studies of the School of Forest Resources and Conservation at the University of Florida. The integrated and cooperative research program is focused on assessing the environmental and site impacts of intensive silvicultural management practices. This report covers the information obtained to date from five

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forested watersheds treated in a range of harvest and site preparation intensities from the undisturbed control to total-tree harvest and land clearing for forest regeneration.

PROCEDURES

Five watersheds were constructed and instrumented in the pine flatwoods landscape of Bradford County in north-central Florida (fig. 1). Three larger watersheds (WS1 = 49, WS2 = 67, and WS3 140 ha) were isolated by roads and provided with a network of rain gages and water table monitoring wells during 1978. Recording flumes in the outlet drainages measured runoff and provided for automatic water sampling. A central weather station recorded standard climatic variables and contained a wet:dry fall collector for the National Atmospheric Deposition Program (Riekerk et al. 1979). Two smaller watersheds (WS4 = 3.8 ha and WS5 = 4.2 ha) were similarly constructed and instrumented during 1980, but separated from each other by a 1-m- deep plastic sheet (Riekerk and Gain 1982).

After 12 monthly observations for pretreatment calibration, the watersheds received treatments according to table 1. The control, watershed 3, remained undisturbed. Watershed 1 was manually harvested to remove pulpwood bolts.

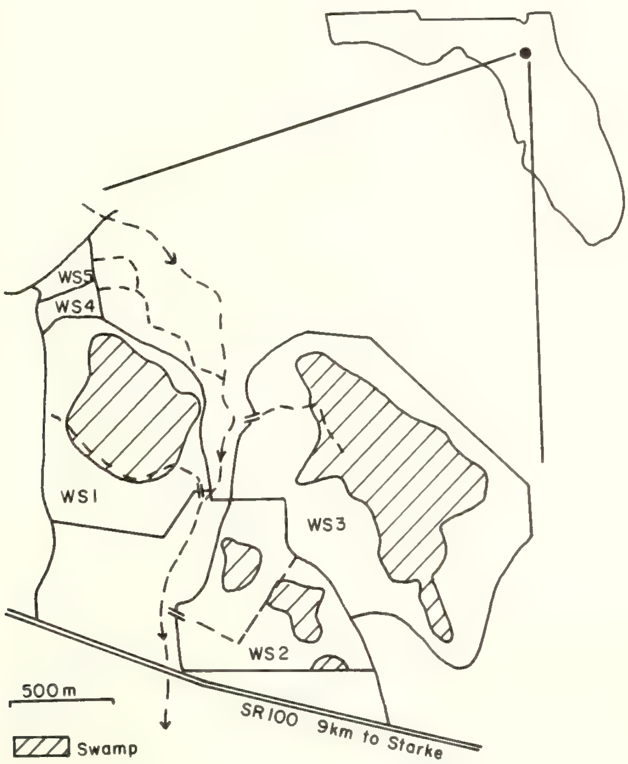

Figure 1--Bradford Forest watersheds

Residual slash and vegetation were chopped twice and the site bedded and planted to slash pine (*Pinus elliottii* Engelm.) in standard pulpwood spacing. Watershed 2 was mechanically harvested and tree-length logs were removed for pulpwood. Remaining plant debris was burned and the residuals windrowed. Cleared areas were bedded and planted to standard pine pulpwood prescriptions. Watershed 4 was mechanically harvested to remove all aboveground tree biomass off site (whole-tree harvest). Residual plant debris was chopped and burned, and the site bedded and planted to standard pine pulpwood prescriptions. Watershed 5 also was mechanically harvested to remove whole-tree biomass, but included stump extraction and removal (total-tree harvest). Remaining plant debris was windrowed and burned, and the bare site furrowed and planted to *Eucalyptus viminalis* in coppice fuelwood density.

Harvesting was restricted to the machine-accessible pine forest sites. As a consequence 41 percent of watershed 1 remained in undisturbed swamp vegetation. Furthermore, the low- intensity site preparation resulted in a rapid regrowth of weeds and sprouts. The undisturbed swamp area of watershed 2 amounted to 26 percent of the area. The planting sites remained sparsely vegetated during the first growing season. The control watershed 3 contained a large swamp covering 47 percent of the total area. The small watersheds 4 and 5 contained no swamps.

Standard vegetation biomass and soil sampling and nutrient assessment procedures have been used as reported by others (Conde et al. 1979, Morris 1981). Water analyses followed standard procedures (Taras et al., 1971).

Table 1--Timing of operations on experimental watersheds

Operation	WS 1	WS 2	WS 4	WS 5
Harvest	Nov 78	Nov 78	Jan 81	Jan 81
Chopping	Apr & Oct 79		Jan 82	Jan 81
Stumping		Jan 79[1]		May 81
Burning		May 79	Feb 81	May 81
Windrowing		Jun 79		Jun 81
Harrowing		Aug 79		
Bedding	Oct 79	Oct 79	Feb 81	Aug 81
Planting	Nov 79	Nov 79	Mar 81	Sep 81

[1] Old-growth turpentine stumps only.

RESULTS

Hydrology

The hydrologic data have been summarized in table 2 and show the decreasing trends of the successive drought years after 1978. Detailed analyses of runoff water yields and stormflows show a significant first-year (1979) increase only from the high-intensity treatment of watershed 2 (Swindel et al. 1982). First-year water yield from the harvested areas of watershed 2 amounted to 426 percent of that predicted from the control. First-year water yield from the low-intensity treatment of watershed 1 was about half as much. Annual water yields from both watersheds were back to baseline levels during the second year (1980) after treatments started. The severe drought conditions of the third year (1981) made predictions impossible for all watersheds including the newly treated watersheds 4 and 5.

Vegetation removal reduces the evapotranspiration pathway resulting in more water available for soil moisture raising water table levels. This is evident from the water table patterns of Figure 2. Draw down of the water table by the intact forest of control watershed 3 is especially evident during drought periods.

Runoff from these flatwoods is largely controlled by emerging water tables. Reasonable correlations between peak flow (Q m^3/sec) of the runoff, precipitation (P cm), and water table level (W m above msl) for the wet year of 1978 were:

WS1 $Q_1 = 32.4\ P - 5.8\ W - 23.2 \quad R^2 = 0.78$

WS2 $Q_2 = 48.8\ P - 20.5\ W - 25.0 \quad R^2 = 0.88$

WS3 $Q_3 = 18.1\ P - 6.5\ W - 12.4 \quad R^2 = 0.83$

Table 2--Hydrologic summary (cm/yr)

	Total WS observ.	Total WS predic.[1]	Cut area calcul.[2]	Percent change[3]
1978				
Precip.	154.2			
WS1 Runoff	61.7			
WS2 Runoff	65.2			
WS3 Runoff	58.3			
1979				
Precip.	126.2			
WS1 Runoff	10.7	4.3	15.1	251
WS2 Runoff	20.6	5.0	26.1	422
WS3 Runoff	5.4			
1980				
Precip.	126.1			
WS1 Runoff	16.7	19.1	15.0	-21
WS2 Runoff	17.5	20.6	16.5	-20
WS3 Runoff	19.3			
1981				
Precip.	86.6			
WS1 Runoff	0.9	0		
WS2 Runoff	3.1	0		
WS3 Runoff	0.1			
WS4 Runoff	1.2			
WS5 Runoff	0.6			

[1] $Q_1 = 1.130\ Q_3 - 0.338$, $R^2 = 0.99$
$Q_2 = 1.165\ Q_3 - 0.221$, $R^2 = 0.99$
Where Q = monthly runoff.

[2] Calcul. Q = (observ. Q x Total WS area - Predic. Q x Pond area)/Cutover area.

[3] Percent change = 100 (Calcul. Q - Predic. Q)/Predic. Q.

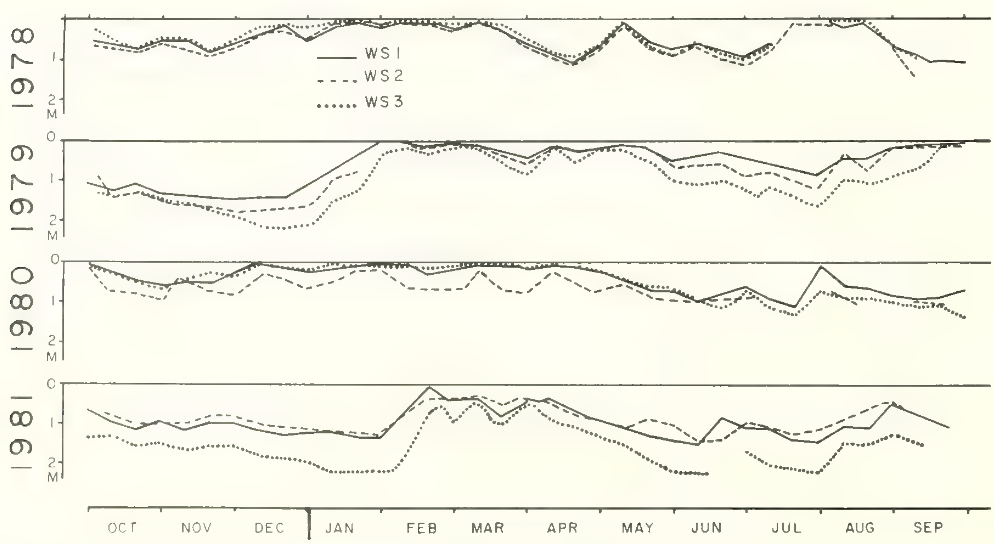

Figure 2--Water table levels of the Bradford Forest watersheds

Table 4--Volume-weighted average pH, nutrient concentration, and suspended sediments in precipitation (PPT) and runoff (RO)

	pH	NH_4N	NO_3N	TKN	PO_4P	TP	K	Ca	Mg	SSed
					(ppm)					
1978 PPT	4.87	.16	.34	.52	.01	.05	.13	.71	.49	--
WS 1 RO	3.68	.11	.04	.41	.04	.06	.15	.52	.71	37.1
WS 2 RO	4.15	.10	.05	.18	.02	.03	.25	.88	.64	44.2
WS 3 RO	3.79	.10	.03	.86	.02	.03	.18	1.16	.70	55.8
1979 PPT	5.02	.05	.16	.40	.00	.02	.03	.16	.06	--
WS 1 RO	3.63	.05	.03	1.35	.03	.02	.55	.37	1.13	5.0
WS 2 RO	4.04	.12	.07	1.11	.02	.02	.90	.94	1.05	14.4
WS 3 RO	3.79	.22	.04	1.56	.03	.02	.18	.26	.98	2.7
1980 PPT	4.81	.11	.20	.49	.00	.03	.07	.18	.08	--
WS 1 RO	3.58	.06	.04	1.45	.03	.05	.25	.38	.77	3.7
WS 2 RO	4.25	.08	.03	.87	.01	.02	.45	.89	.66	11.4
WS 3 RO	3.85	.07	.02	1.03	.02	.02	.05	.37	.53	2.7
WS 4 RO	4.06	.20	.02	.62	.02	.03	.20	1.10	1.90	
WS 5 RO	4.24	.27	.02	.86	.04	.04	.30	1.30	1.20	
1981 PPT	4.66	.16	.22	.41	.00	.02	.04	.17	.01	--
WS 1 RO	3.54	.15	.02	1.13	.00	.02	.78	.20	1.43	5.4
WS 2 RO	4.19	.09	.26	1.05	.00	.01	.71	1.69	.71	3.6
WS 3 RO	3.81	.13	2.31	1.18	.00	.01	.26	1.38	1.57	7.0
WS 4 RO	4.43	.46	.16	.95	.01	.01	1.40	2.60	2.60	
WS 5 RO	4.31	.46	.12	1.03	.01	.01	1.90	1.80	2.00	

Table 5--Annual nutrient and sediment fluxes with precipitation (PPT) and runoff (RO)

	NH_4N	NO_3N	TKN	PO_4P	TP	K	Ca	Mg	SSed
				(ppm)					
1978 PPT	2.76	4.39	12.57	.39	2.88	2.68	10.97	4.04	--
WS 1 RO	.45	.15	1.70	.17	.23	.62	2.14	2.96	154.2
WS 2 RO	.42	.19	1.73	.13	1.03	9.80	2.62	3.93	182.2
WS 3 RO	.57	.57	.18	4.78	.11	1.01	6.47	3.93	311.0
1979 PPT	1.91	2.33	5.95	.02	.06	3.11	2.96	3.72	--
WS 1 RO	.07	.05	1.19	.05	.03	.78	.53	1.60	7.1
WS 2 RO	.30	.17	2.77	.04	.04	2.25	2.53	2.64	36.0
WS 3 RO	.23	.04	1.68	.03	.02	.19	.28	1.06	2.8
1980 PPT	1.80	1.95	4.04	.07	.35	1.25	.47	1.53	--
WS 1 RO	.06	.04	1.53	.03	.05	.26	.40	.82	3.9
WS 2 RO	.04	.02	.48	.01	.01	.25	.49	.37	6.4
WS 3 RO	.08	.03	1.21	.02	.03	.06	.44	.62	3.1
1981 PPT	1.41	1.89	3.51	.01	.19	.36	1.48	.61	--
WS 1 RO	.01	.00	.10	.00	.00	.07	1.11	.13	.5
WS 2 RO	.02	.08	.32	.00	.00	.22	.51	.22	1.1
WS 3 RO	.00	.03	.01	.00	.00	.00	.02	.02	.1
WS 4 RO	.06	.02	.11	.00	.00	.17	.31	.31	
WS 5 RO	.03	.01	.06	.00	.00	.11	.11	.12	

Water Quality

Runoff water quality was monitored during the calibration and treatment years as summarized in table 4. Considerable variability is present, but a few large differences from the control are apparent.

A large decrease of ammonium nitrogen levels in runoff was generated by the low-intensity treatment on watershed 1 during the first year. Potassium, calcium, and suspended sediments levels were increased especially by the high-intensity treatment on watershed 2. Elevated potassium levels persisted during the following 2 years.

Similar increases of cation nutrient levels were apparent in runoff from watersheds 4 and 5 during 1981. In contrast to the low-intensity treatment effect, the ammonium nitrogen levels in runoff from watersheds 4 and 5 were higher than the control during both calibration and treatment years.

The severe drought year (1981) generated very high levels of nitrate nitrogen in runoff from the control watershed 3. This unit contained a large swamp, which dried up exposing the accumulated muck to air. During the same year, the calcium level in runoff from the low-intensity treatment Watershed 1 was much lower than during the wet years.

Nutrient Fluxes

The increases in water yields because of vegetation removal partly diluted the treatment effects on water quality. Nutrient flux calculations provide for a sharper definition of treatment effects. Nutrient fluxes of table 5 have been calculated from hydrologic fluxes and water quality data.

This information confirms the changes in water quality but shows additional differences because of treatments. The large increase of runoff during the first year from high-intensity treatment on watershed 2 made annual nitrate export much higher than that from the control watershed 3. Annual Kjeldahl- nitrogen export from the same watershed was much less than that of the control during the second year after treatments started. Interestingly, the sharp increase of nitrate levels in runoff from the control watershed during the drought year of 1981 was offset by the relatively little amount of runoff. The same phenomena also account for exceptionally low fluxes of other nutrients with runoff from the control watershed 3.

Table 6 documents the information on biomass nutrient contents and removals. Total ecosystem contents differ somewhat between the two subsets of Watersheds 1, 2, 3, and 4, 5, partly because the latter two units include stump biomass and do not contain swamps.

An overwhelmingly large export of nutrients occurred with the harvested biomass removals. The pulpwood harvests from watersheds 1 and 2 removed about half of the biomass on the site. The whole-tree harvest on watershed 4 removed 8 percent more, and the total-tree harvest (including stumps) on watershed 5 removed about 16 percent more than the pulpwood harvests. Phosphorus and calcium exports with the more intensive whole-tree and total-tree harvests were about 10 percent higher than the pulpwood harvests. Exports of other major nutrients increased by about 5 percent.

DISCUSSION

One interesting result of the study was that treatment effects on runoff are short lived. The induced changes in water yields and water quality became significantly less within 1 year after harvest and regeneration.

First-year water yield increases (Δq centimeters per year) from hardwood forest lands after harvesting have been summarized by Douglass and Swank (1975) in relation to basal area removed (X_1 percent) and potential annual insolation (X_2 macrolys):

$$\Delta q = 0.0057\ (X_1/X_2)^{1.446}\ . \qquad (1)$$

At 30° N latitude in north Florida (0.282 macrolys) the first-year water yield increase for a clearcut area comes to 28 cm/yr. The low value of 21 cm/yr water yield increase after the high-intensity treatment on watershed 2 (table 2) appears to be partly because of generally smaller storms during that year and partly because the equation was developed for deciduous forests.

Such water yield manipulation is useful for watershed management in that some nonstructural regulation of runoff becomes possible by carefully patterning annual water yields (q) from clearcut areas during a management rotation (R). A change (ΔQ) of total annual catchment water yield (Q) may be predicted from the equation:

$$\Delta Q/Q = 1/R * \Delta q/q\ . \qquad (2)$$

For example, for a 25-year management cycle, 4 percent of the total catchment is harvested each year. According to table 2, harvesting and site preparation could triple first-year water yields from a pine flatwoods area. This could result in an 8 percent increase in annual water yield from the total catchment. If the water yield increase of a harvest area is persistent, the total catchment yield increase is proportionally larger.

Vegetation removal interrupts the evapotranspiration pathway and increases soil moisture and water table levels. The rather close relationships among peakflow,

Table 6--Biomass and nutrient contents and removals

	Biomass	N	P	K	Ca	Mg
	mt/ha	kg/ha				
Pre-harvest Content						
WS1, WS2, WS3:1/						
Stems	64.5	66	6.0	22.1	90	19.5
Crowns	9.1	44	3.6	13.5	28	7.4
Understory	6.7	30	2.1	7.1	32	7.4
Forest floor	34.2	271	9.7	9.3	96	20.2
Total	114.5	351	21.4	52.0	246	54.5
Rooting Zone2/		2959	24.3	81.6	396	207.8
WS3, WS4:3/						
Stems	99.0	97	8.9	31.6	132	28.7
Crowns	13.2	65	5.3	19.6	35	1.01
Hardwoods	4.7	45	2.2	11.0	28	15.5
Understory	5.6	32	2.2	10.5	33	8.0
Stumps	25.5	25	2.2	8.1	34	7.4
Forest floor	33.6	277	9.9	9.2	96	19.0
Total	181.6	541	30.7	90.0	358	88.7
Rooting Zone2/		3400	12.0	77.0	465	142.5
Harvest Removals						
Pulpwood1/	57.4	59	5	20	80	17
% of Total	50.1	16.8	23.4	38.5	32.5	31.2
Whole-tree3/	105.6	110	10	35	138	31
% of Total	58.1	20.3	32.6	38.9	38.5	34.9
Total-tree3/	119	120	11	39	157	35
% of Total	65.7	22.2	35.8	43.3	43.9	39.5

1/From Morris and Pritchett 1982.
2/Double-acid extractable P, K, Ca and Mg.
3/From Riekerk and Gain 1982.

Table 7--Summary of published water quality and export data for watersheds in Florida.

Site	TN	NO_3	NH_4N	PO_4	TP	SS	TN	NO_3N	NH_4N	PO_4	TP	SS
	(ppm)						(kg/ha/yr)					
NW Florida: Carrabelle1/												
100% forest	0.85	0.01	0.02	0.002	0.032	6	4.8	0.09	0.22	0.04	0.22	44
100% clearcut: year 1	2.69	0.05	0.43	0.074	0.284	137	10.9	0.20	1.75	0.30	0.81	550
year 2	1.52	0.02	0.07	0.002	0.033	28	9.6	0.13	0.44	0.01	0.21	178
year 3	0.09	0.01	0.03	0.001	0.030	8	6.5	0.10	0.20	0.01	0.20	40
N Florida: Tallahassee2/	--	0.05	0.04	0.092	0.099	48	--	0.08	0.07	0.15	0.17	40
52% forest - 48% agric	--	0.31	0.08	0.047	0.060	443	--	0.46	0.13	0.08	0.11	514
12% forest - 88% urban	--	0.08	0.07	0.078	0.087	1,194	--	0.22	0.17	0.18	0.22	2,376
NC Florida: Gainesville3/												
68% forest - 37% agric												
year 1	2.73	0.22	0.21	0.58	0.63	--	1.4	0.12	0.11	0.30	0.33	--
year 2	1.87	0.10	0.07	0.59	0.77	--	1.6	0.09	0.07	0.52	0.68	--
S Florida: Taylor Creek4/												
30% forest - 60% agric	--	0.17	--	0.33	--	--	--	0.40	--	1.65	--	--
20% forest - 70% agric	--	--	--	--	--	--	--	0.37	--	0.84	--	--
78% pasture - 21% dairy	--	0.15	--	0.32	--	--	--	1.61	--	6.95	--	--

1 Source: Hollis et al. 1979; Fisher 1981.
2 Source: Burton et al. 1977.
3 Source: Campbell 1979.
4 Source: Stewart et al. 1978.

precipitation, and water table level of this study corroborate findings for low-lying, coastal zone, pine forest lands elsewhere in the southeastern United States (Williams and Lipscomb 1981). Runoff only begins when the water table rises to the bottom of drainages with subsequent upstream and overland expansion of the variable-source area (Hewlett 1961). Such relationships are useful for forest water management without having to measure stream flow.

The observed changes in water quality associated with treatment effects are comparable to those reported by others (table 7). Disturbances by agricultural and urban activities appear to cause far more water quality degeneration. Of special interest in the Florida forest watershed data is the low level of nitrates and relatively small response to silvicultural activities in comparison to data from upland watersheds elsewhere. It is likely that the poorly drained flatwoods soils inhibit nitrification and/or promote denitrification processes (Morris and Pritchett 1982). The only exception in the Florida data is the significant but low-level first-year nitrate loading by the high-intensity treatment on watershed 2 (table 4).

Runoff acidity of pH 4 from humic acids is the norm rather than the exception in these dark-colored waters. The hydrogen ion sources obliterate the contribution of protons from bicarbonate. Treatments appear to have little effect on pH partly because of dilution by the increased runoff.

The low-intensity treatment of watershed 1 caused a first-year decrease of ammonium-nitrogen in runoff, but that in surface soil solutions increased (Morris 1981). This suggests a strong conservation mechanism such as uptake by the rapidly growing weed vegetation. High-intensity mechanical site preparation or herbicide applications for weed control counteract this nutrient conservation effect.

Disruption of the soil-vegetation complex appears to lead to higher mobility of cation nutrient elements as evidenced by the data. Of particular interest is the highly significant and persistent increase of potassium levels in runoff proportional to treatment intensity. Potassium is known to be a biologically mobile element but usually becomes rapidly and tightly fixed by soil minerals. The weathered sandy soils of the flatwoods presumably lost long ago the potassium-fixing minerals through acid leaching. A large release of potassium therefore occurs after destruction of the biologically active vegetation.

Suspended sediment production because of treatments is significant and proportional to treatment intensity, however, levels remain very low as compared to data from upland watersheds. Sandy bedload sediments from the watersheds were derived mainly from the immediate surroundings of the traps with some contributions from nearby road ditches. There was no significant difference because of treatments on these bedload movements.

The annual nutrient input with precipitation, loss with runoff and export with biomass have been summarized in table 8. It is obvious from this data that the periodic biomass export represents the major pathway for nutrient losses from the managed sites. The commercial stem-only harvests for pulpwood appear to keep the overall nutrient balance positive. Only calcium fertilizer at the annual rate of 1.3 kg Ca/ha would be required for another rotation. The whole-tree removal significantly increases nutrient depletion of the site, especially that of phosphorus and calcium. Calcium phosphate fertilizer applications at the rate of 0.2 Kg P and 4.4 kg Ca per hectare per year would be required to at least prevent long-term site degradation. The additional removal of stumps by total-tree harvesting severely depletes the growing site. Annual fertilizer additions would have to be 5.9 kg N, 0.2 kg P, 0.1 kg K, 4.4 kg Ca, and 0.4 kg Mg per hectare to sustain long-term site productivity.

These fertilizer estimates are based on data for nutrient losses from first-rotation forest lands. Increased biomass removal also may deplete the organic matter content of the soil and with it diminish the nutrient retention powers. Utilization of carbon-rich sewage sludge as a soil amendment could correct this.

Table 8--Estimated long-term inputs and outputs (40-year stand)

	N	P	K	Ca	Mg
	---------	kg/ha/yr	-----------		
Water					
Precip. 1979-1981	6.65	0.20	1.57	1.64	1.95
Runoff 1978-1981	1.00	.02	.08	.25	.75
Net	5.56	.18	1.49	1.39	1.20
Harvest[1/]					
Stem-only	1.97	.17	.67	2.67	.57
Net	3.59	.01	.82	-1.28	.63
Whole-tree	5.40	.30	1.10	4.77	1.07
Net	.16	-.12	.39	-3.38	.13
% Increase[2/]	174	76	64	79	88
Complete-tree	11.50	.43	1.57	5.77	1.57
Net	-5.94	-.25	-.08	-4.38	-.37
% Increase[2/]	484	153	134	116	175

[1/] Annual output = harvest/stand age.
[2/] Percent increase over stem-only harvest.

CONCLUSIONS

Present-day silvicultural practices pose little threat to environmental and site values of flatwoods forest lands in Florida. Water yield increases and water quality degradation are not very large and of rather short duration.

More intensive silvicultural practices of aboveground and total-tree harvesting severely disturb these forest lands. Rates of fertilization proportional to severity of nutrient depletion are suggested using slow-release calcium phosphate or carbon-rich waste materials.

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NITROGEN SUPPLY FOR FORESTS INTENSIVELY MANAGED FOR FIBER AND ENERGY IN THE ATLANTIC COASTAL PLAIN: A MODELING APPROACH

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ABSTRACT: In the Southeast, biomass energy will probably be restricted primarily to direct burning of wood fuels by forest industry. Whole-tree harvesting and frequent thinnings in southern pine plantations are likely to become more common.

Comparisons of nitrogen utilization efficiency (kg biomass/kg N) showed slow growing conifers on poor sites were the most efficient users of nitrogen. Productivity efficiency (kg/yr/kg N) indicated that if the amount of available land is limited, short rotations of loblolly pine or eastern cottonwood should be emphasized.

INTRODUCTION

Forest industry will be the primary user of wood energy in the southeastern United States. Much of the material will be harvested from industry-owned land. Staebler (1979) indicated that fuelwood use will increase the use of pine tops and roots and unmerchantable hardwoods. This paper examines the nutrient cycling impacts of increased harvesting rates for loblolly (Pinus taeda L.) and slash pines (Pinus elliottii Engelm.).

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Increased forest utilization will increase the rate of nutrient removal from the sites being harvested. Harvesting of the entire aboveground portion of trees, and possibly taproots, significantly increases the quantity of nutrients removed from the site in comparison to standard stem-only harvests. Jorgensen et al. (1975) estimated that changing from a conventional stem-only harvest to whole-tree (aboveground biomass) harvest on a 16-year-old loblolly plantation would increase N removal from 104 to 254 kg/ha, P removal from 13 to 30 kg/ha, and K removal from 61 to 165 kg/ha. Removal of taproots would increase the values to 282, 37, and 202 kg/ha, respectively. Pritchett (1981) showed that changing from conventional to whole-tree harvesting of 25-year-old slash pine would increase losses of N, P, K, Ca, and Mg by 89, 118, 85, 73, and 118 percent, respectively. Switzer and Nelson (1972) showed that whole-tree harvesting increased N removal from 242 to 384 kg/ha, P removal from 17 to 27 kg/ha and K removal from 168 to 212 kg/ha on 20-year rotations of loblolly pine. Although not all inclusive, these data clearly show that whole-tree harvesting increases the loss of important nutrients from 50 percent to more than double the losses associated with conventional stem-wood harvests.

Intensive harvesting and site preparation may change nutrient reserves through increased losses because of changes in the physical character of the soil. The most highly cited impact is that at Hubbard Brook, N.H. (Likens et al. 1970), where increased nitrification led to larger runoff losses of nitrogen, potassium, calcium and magnesium. Large changes have not been found in the Southeast (Riekirk et al. 1978, Riekirk 1982) although Swank and Douglass (1977) found small persistent increases in nitrate concentration after site disturbances.

Intensive site preparation can cause a major redistribution of on-site nutrients. Morris et al. (1981) showed that windrowing of slash transferred 376 kgN/ha, 17.6 kgP/ha, and 27.3 kgK/ha into the windrows. In addition, Pritchett (1981) found a delayed release of nutrients in areas that were chopped in comparison to areas that were windrowed. Burger (1979) estimated that total site N reserves were 479 kg/ha less on a windrowed site than on an adjacent chopped site. Webber (1978) indicated that up to 1400 kg/ha of nitrogen could be removed from pumice soils in New Zealand by windrowing.

Intensive culture and increased utilization will greatly increase the rate of nutrient removal from forest sites. The impact of this nutrient drain on future site production will depend on: (1) the rate of input of nutrients, and (2) the ability of the soil to resupply these nutrients.

Kimmins (1977) stated that a number of questions must be answered in order to evaluate the consequences of increased nutrient removal. What portion of site nutrients, both total and available, are removed? How rapidly do the nutrients recycle? How rapidly are either total or available pools replenished? What is the requirement of the subsequent crops? What is the magnitude of other harvest losses? How frequently will these losses occur? All of these questions cannot be answered relative to the wide range of sites in the coastal plain or for the varieties of contemplated harvesting strategies. A model of nitrogen use for a single system will be used to illustrate potential problems in assessing the impact of whole-tree harvesting and to identify research needs.

MODEL DEVELOPMENT

The model presented here assumes that nitrogen is the limiting nutrient and that growth rate will be depressed if nitrogen supply is less than nitrogen requirements. These two variables will be considered as rates. For example, the nitrogen requirement in a given year is assumed to be all the nitrogen incorporated into net primary production that year. Likewise, nitrogen supply is the sum of the rates at which nitrogen in each system pool (living biomass, forest floor, soil organic matter, etc.) passes into an available compound (NO_3, NH_4) during cycling processes. The time step used in this model will be 1 year and nitrogen requirements and supply will have the units of kilograms per hectare per year.

The model will be used to evaluate a silvicultural system proposed by Koch (1980) to maximize production of both energy and fiber of loblolly pine plantations. In this system pines are planted or seeded at a rate of 24,700 trees/ha. At age 5 the stand is thinned to 3,700 trees/ha by a mobile chipper. The remainder is thinned periodically to attain a final stocking of 150 to 250 trees/ha at age 35. All remaining thinnings and the final harvest are whole-tree harvests with taproots included. This system is expected to produce 327 t/ha of pulp and building materials plus 105 t/ha of fuel per rotation. Both the nitrogen supply and nitrogen requirements of this system were evaluated by use of the model developed on the basis of the following information and assumptions.

Biomass growth and nitrogen content from 0 to 5 years were taken from White and Pritchett (1970). Aboveground biomass growth, disposition among tree parts, and nitrogen concentrations were taken from Smith et al. (1963) in 5-year increments. Yield values by Koch (1980) were 3.4 times larger than Smith et al. (1963. Biomass values were adjusted to fit Koch's (1980) estimates. Growth, during a 5-year interval, was assumed to be linear. Annual foliage growth was calculated under the assumptions that needles persist for 2 years and growth is sufficient to produce a linear (over 5 years) change in foliar biomass. Root biomass was calculated as 33 percent of aboveground biomass and distributed equally between taproots and laterals as assumed by Koch (1980). These numbers differ slightly from data of Wells et al. (1975) but agree quite well with slash pine data from White and Pritchett (1970). Death of fine roots was assumed to be 38 percent of the lateral root biomass. The only applicable study of fine root turnover, by Kinerson et al. (1977), showed a death rate of 9,000 kg/ha·yr at age 16. This was equivalent to 38 percent of lateral root biomass in the model, and this percentage was assumed to be constant throughout the rotation.

Sources of nitrogen in the model were rainfall, dry fallout, fixation, litter decay, fine root decay, translocation (including throughfall and stemflow), release from forest floor, and release from the soil pool. Rainfall input was 9.8 kgN/ha·yr.[1] Fixation rate was assumed to be 5 kg/ha·yr (Pritchett 1981). This rate is higher than that measured by Jorgensen et al. (1975) but below that observed by Jorgensen and Wells (1971).

Litter decay for the first 8 years was taken from graphs in Jorgensen et al. (1980). After 8 years, the litter was incorporated into the forest floor pool which released nitrogen at a rate of 3 to 10 percent per year depending on stand age (Jorgensen et al. 1980). The decay rate for fine roots was assumed to be the same as the decay rate for litter. After 8 years, the fine roots were

[1] Mean of eight values for Southeast U.S. (Brinson et al. 1980, Rolfe et al. 1978, Riekirk 1982, Swank 1979).

included in soil organic matter which was assumed to release nitrogen at a rate of 5 percent per year. Translocation was assumed to occur at the end of the first year and was assumed to be the difference between the N concentration in fresh needles from Smith et al. (1963) and the concentration in litterfall as measured by Jorgensen et al. (1980). Fine roots were also assumed to translocate N back to laterals at the same rate as needles to shoots. Root translocation has not been measured but Aber et al. (1978) also assumed root translocation to equal needle translocation. Initial forest floor and total soil nitrogen pool data were taken from Jorgensen et al. (1975)

These assumptions and data were used to determine both nitrogen requirements and supply throughout one and one-half 35 year rotations by use of an accounting model. The stand was thinned at ages 15, 20, 25, and 30, with equal biomass removal at each thinning. The model began at year 0 with a soil and forest floor N pool of 2060 kg/ha. Nitrogen requirements to grow each biomass component were computed for each year. Nitrogen supply was computed and excess nitrogen was returned to the soil organic pool before supply was computed for the succeeding year (fig. 1, 2, and 3).

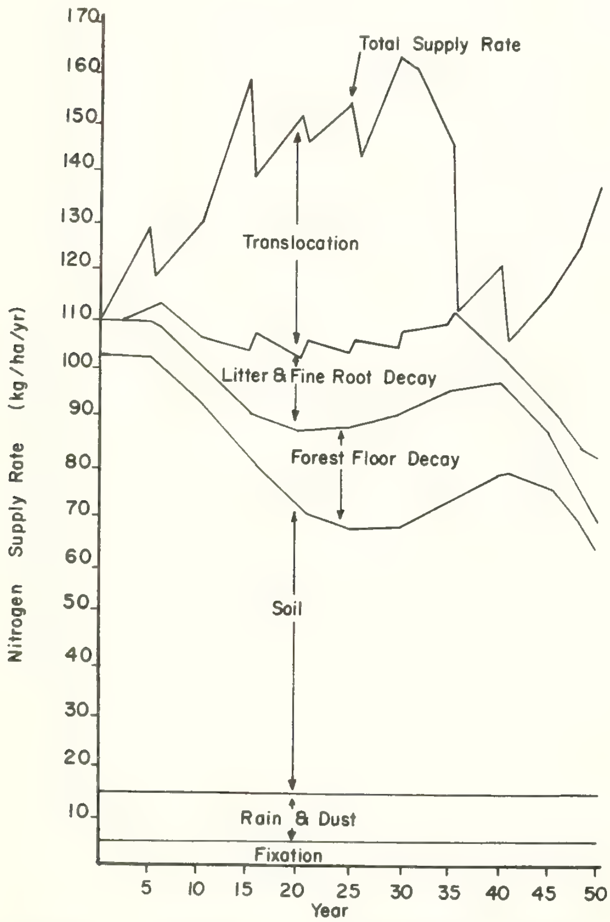

FIGURE 1. SOURCES OF NITROGEN SUPPLY

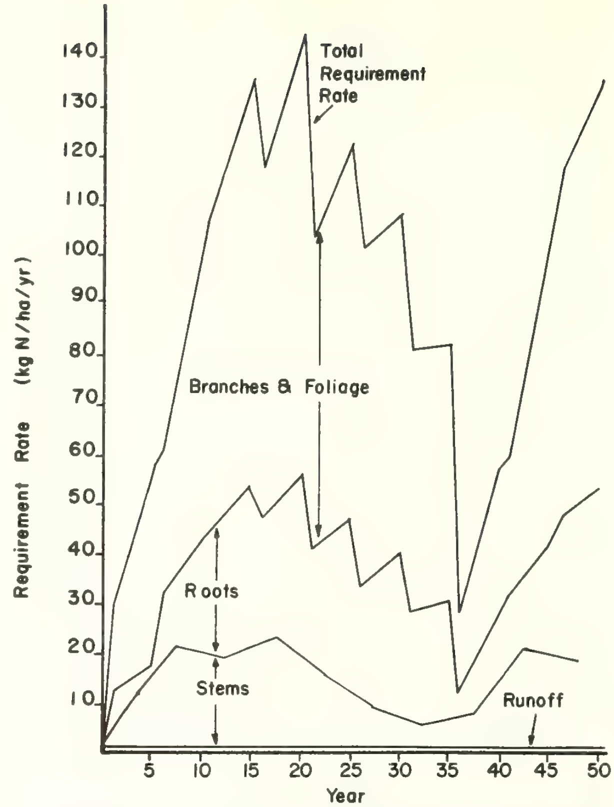

FIGURE 2. NITROGEN REQUIREMENTS BY TREE PARTS

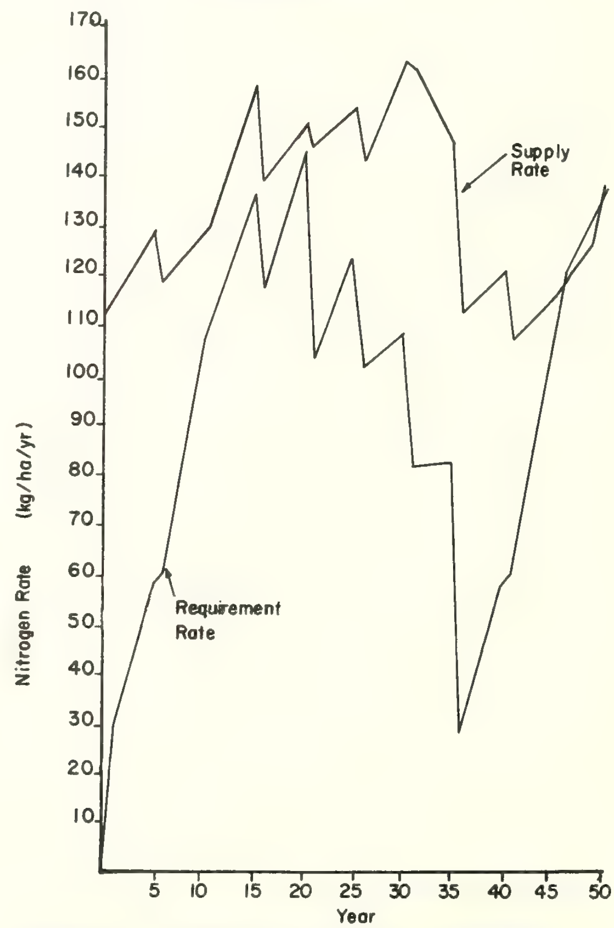

FIGURE 3. PREDICTION OF NITROGEN SUPPLY DEFICIT

RESULTS

Comparisons of simulation results to results of other studies not used in the preparation of the model showed that the model provides a reasonable reflection of loblolly growth on good sites (table 1). In general, the model agreed with data of Nemeth (1973), Larson et al. (1976), and Jorgensen et al. (1975), but were higher than data of Switzer and Nelson (1972). Predicted foliar biomass was higher than reported during the middle of the rotation, predicted root biomass was higher than reported, and root growth and death values could not be compared.

This model predicts that the supply rate will fall below the rate of requirements by year 12 of the second generation. It predicts that the system proposed by Koch (1980) will require nitrogen supplements during the second and subsequent generations. Modeling was discontinued at age 15 of the second generation. The model points out several areas where future research is needed.

Accurate estimates of the rate of soil organic nitrogen availability are the most important factors in nitrogen supply. The rate of nitrogen supply decreased even though the total nitrogen pool declined by only 270 kg/ha (2060 to 1790 kg/ha). The critical factor was the size of the soil organic N pool which had declined from 1753 kg/ha to 1091 kg/ha. The large size of this pool and the assumed availability rate are the reasons for timing of the nitrogen deficit. If the availability rate had been 4 percent, the deficit would have occurred during the first rotation and had the rate been 6 percent, the deficit would not have occurred until the third rotation. Evaluation of the rate of availability from soil organic matter and the processes which determine this rate should be a high priority for future research.

The input of nitrogen from decomposing litter early in the rotation requires more study. Jorgensen et al. (1980) measured the decay rates of freshly fallen litter and older litter only in stands. The decay rate of older litter and the forest floor after full tree harvesting could be considerably different. Although cycling of nitrogen from accumulated litter is important in stands over 20 years old, the supplies of new stands are determined by litter on the forest floor prior to harvest. The mineralization rate of this older litter as it is exposed by harvesting needs to be studied.

Root nutrient relations have not been measured for loblolly pine systems. Translocation is an important function in retaining nutrients needed for foliar growth (Switzer and Nelson 1972). In the model, 28 percent of the available N came from translocation, throughfall, and stemflow during the critical period of 10-15 years when N demands are greatest. In the model, it was assumed that dying roots translocated N back into the tree at the same rate as needles do before abscission. This assumption is pure speculation and, if untrue would increase the needs of the tree by 10-15 kg/ha•yr. The rate of decay of dead roots was also speculative. Turnover rate and the decay rate of fine roots will need to be established before the needs of the new stand can be determined.

The role of understory plants in nitrogen cycling in subsequent rotations needs to be defined. No data compatible with the modeling

Table 1--Comparison of values predicted by the model with independent data

	Age and source of data							
	Age 10		Age 13		Age 16		Age 20	
Component	Nemeth 1973	Model	Larson et al. 1976	Model	Jorgensen et al. 1975	Model	Switzer & Nelson 1972	Model
Total biomass (mt/ha)	91	98	109	159	192	191	105	223
Aboveground biomass (mt/ha)			98	115	156	144	90	168
Litterfall (mt/ha/yr)	3.6	3.8					5.0	7.2
Foliar N (kg/ha)			80	131	82	156		
Total N requirement (kg/ha•yr)					117	136	70	117
Foliar N requirement (kg/ha•yr					58	76	60	86

approach used here was found. Also the role of early successional plants and of nitrogen fixing plants in early growth of pines needs to be evaluated.

The model shows that a decline in growth may occur if net output exceeds net input of a nutrient. Such a decline may occur long before a significant portion of the total pool is removed. Whole-tree harvesting has been shown to result in a negative net balance in many studies: N in loblolly pine (Waide and Swank 1975, 1977), P and K in slash pine (Pritchett 1981), N, P and K in cottonwood (Populus deltoides Barter. ex Marsh.) (White 1974), and P in sycamore (Platanus occidentalis L.) (Wood et al. 1977). Widespread use of whole-tree harvesting without nutrient replacement does not appear tenable. Declines in growth may appear more rapidly than had been previously assumed.

Increased utilization will require replacement of nutrients. Nitrogen can be applied in an available form, a slow release form, or by nitrogen fixing plants. If these expensive procedures are to be pursued they will require some measures of efficiency. Hanson and Baker (1979) and Marion (1979) used a measure of efficiency to evaluate alternative systems. Their measure was kilograms biomass per kilograms nitrogen, which is an averaged nitrogen concentration. Slow-growing conifers on poor sites are the most efficient users of nitrogen (table 2).

Efficient use of land and capital require fast growth rates so a more realistic efficiency index should account for productivity. Productivity efficiency (kilograms biomass per year per kilogram nitrogen used, table 2) shows that short rotation defoliated harvest of pine and cottonwood produce the greatest growth per unit of nitrogen used. Harvesting of foliage decreases efficiency regardless of the measure used.

The last two entries in table 2 are special cases. Smith et al. (1979) provided results of a field trial growing cottonwood with high rates (20 cm/week) of sewage effluent on a droughty sand in west Florida. This system had the lowest absolute efficiency of any measured, but also had, by far, the highest productivity. Since nutrient removal is advantageous in a sewage disposal system these data suggest a method of doubling the productivity of short rotation biomass harvests (Hanson and Baker 1979).

Sand pine (Pinus clausa (Chapm. ex Engelm.) Vasey ex Sarg.)) is being production tested in Florida[1] because it can produce acceptable yields (3 t/ha·yr) on sites unsuitable for commercial species. The nutrient cycling implications of this system are unknown (the data in table 1 uses needle contents by Brendemuehl (1972), biomass from Rockwood et al. (1980), and nutrient concentration of loblolly stem bark and branches (Metz and Wells 1965). Sand pine probably has a nitrogen efficiency less than loblolly pine systems. If sand pine becomes an important species, studies of how it is able to survive and grow on these presumably poor sites seem warranted.

SUMMARY

Increased utilization by use of whole-tree harvesting and frequent whole-tree thinning results in increased depletion of soil nutrients. In most cases studied, increased utilization will require addition of nutrients by some form of fertilization to maintain similar growth rates in subsequent rotations.

The system proposed by Koch (1980) was studied using a nitrogen cycling model. The model predicted that growth rates in the second rotation would be limited by an inadequate rate of nitrogen supply.

The major limitations of the model were: (1) Koch's growth rates and below-ground biomass estimates are above these in other studies for ages greater than 15 years; (2) the rate of soil organic N availability was the most important factor in determining overall availability; and (3) fine root death, decay, and N translocation require more study before accurate estimates of availability from these sources can be made. In most cases nitrogen supply rates were based solely on nitrogen pool sizes. A more process oriented approach is needed.

Given these limitations the model does point out that growth rates can be reduced before a large decrease in total site nitrogen occurs. Modeling nitrogen supply rates also could be useful in planning judicious use of fertilizer or biological nitrogen fixation. Available fertilizers such as ammonium nitrate would be most appropriate to increase growth when the nitrogen supply rate was low. Biological nitrogen fixation would be most effective in restoring larger amounts of nitrogen to total soil nitrogen.

Estimates of utilization efficiency showed that slow-growing conifers on poor sites use nitrogen most efficiently. If land, capital, and nitrogen are considered, however, short-rotation pine and cottonwood are most efficient. In no case did harvesting of foliage increase efficiency.

ACKNOWLEDGMENT

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[1]Personal communication, W. L. Beers, Buckeye Cellulose Corp., Perry, Fla.

Table 2--Nitrogen utilization efficiencies of various systems and species

	Biomass	Nitrogen removed	Absolute efficiency	Age	Productivity efficiency	Source
	t/ha	kg/ha	kg/kgN		kg/yr / KgN	
Loblolly pine						
Whole-tree and taproot	429	1033	415	35	18.1[1]	This paper
Stem and taproot	302	380	795	35	30.0[1]	
Loblolly pine						
Whole-tree and taproot	185	282	656	16	41	Jorgensen et al. 1975
Defoliated Whole-tree and taproot	178	200	890	16	56	Jorgensen et al. 1975
Stem to 8-cm top	116	104	1115	16	70	Jorgensen et al. 1975
Stem and taproot	114	132	1090	16	68	Jorgensen et al. 1975
Loblolly pine						
Whole-tree	98	180	544	13	13	Larsen et al. 1976
Loblolly pine						
Whole-tree	28	118	237	5	47	White and Pritchett 1970
Pinus radiata						
Whole-tree	141	300	470	12	39	Will 1964
Stem only	118	120	983	12	82	Will 1964
Pinus banksiana						
Whole-tree	137	204	671	65	10	Morrison and Foster 1979
Stem only	90	82	1097	65	17	Morrison and Foster 1979
Picea mariana						
Whole-tree	108	167	647	65	9	Morrison and Foster 1979
Stem only	88	71	1239	65	19	Morrison and Foster 1979
Populus tremuloides						
Whole-tree	167	368	453	40	11	Morrison and Foster 1979
Stem only	147	199	739	40	18	Morrison and Foster 1979
Populus deltoides						
4-years leaf off whole-tree	34	128	265	4	66	Hanson and Baker 1979
10-years leaf off whole-tree	81	214	381	10	38	Hanson and Baker 1979
20-years leaf off whole-tree	184	352	523	20	26	Hanson and Baker 1979
3-years whole-tree sewage applied	178	2463	73	3	24	Smith et al. 1979
Platanus occidentalis						
Leaf off whole-tree	32	160	200	4	50	Hanson and Baker 1979
Pinus clausa						
Whole-tree	32	107	301	12	25	Rockwood et al. 1980 Brendemeuhl 1972

[1]Modified for early harvest.

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MAINTENANCE AND IMPROVEMENT OF FOREST PRODUCTIVITY: AN OVERVIEW

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ABSTRACT: Forest soil productivity can be maintained by judicious management which maintains a vegetative cover, to prevent erosion and retain nutrients, alleviates soil compaction by plowing or subsoiling and restricts the use of fire on impoverished coarse-textured soils.

Forest site productivity is most likely to be increased by cultural techniques that reduce the time to canopy closure. These techniques include providing adequate drainage, controlling weed competition and fertilizing to correct nutrient deficiencies.

INTRODUCTION

Considerable advances in techniques for site preparation and fertilization over the past 50 years have encouraged foresters to dream of a future for silviculture in which the manager's dominion over his site is comparable to that of his counterpart in modern, intensive agriculture. Concomitantly, a fear has arisen that intensification of management and harvesting is departing so far from a dimly perceived natural order that site degradation must result. There is little substance to either the dream or the fear although in future the forest manager almost certainly will be better equipped both to intensify his management and to discharge his responsibility for conservation of the forest environment.

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Productivity, defined here as the cumulative harvestable biomass over the period until mean annual increment is maximized, is the result of the interaction of the genetic potential with climate and soil. Considerable gains may result from changing genetic potential, whether through species and provenance selection or tree breeding. Of the site factors, climate, excepting minor aspects of the microclimate, is not open to manipulation, but we have come to believe that the soil is relatively responsive to management dictates.

MAINTENANCE OF SITE PRODUCTIVITY

In essence maintenance of site productivity amounts to ensuring the continued existence of the soil and maintaining both its rootable depth and nutrient supplying capacity.

Physical Considerations

The preservation of the soil through ensuring unbroken forest cover is one of the oldest

objectives of systematic forest management, and remains a pre-eminent requirement both in mountainous areas and in many of the semi-arid regions of the world. Even in production forests (as against protection forests) the manager may have to take steps to prevent loss of soil. Such steps amount to a list of what should not, rather than what should, be done. For example, roads and associated ditches should not be laid out in ways that might initiate gulley erosion. Plow lines and drains should not be angled too steeply to the contour unless rainfall is known to be light or revegetation rapid. Extraction and site preparation should not leave steep erodible channels or expose light soil to potential wind erosion. Fire should not be used where a significant proportion of the soil consists of thin organic matter over rock.

All these errors are obvious and foresters are trained to avoid them. Less clear is what should be done to preserve rootable volume, a parameter that may be reduced either by a rise in water table level or an increase in soil density. Although documentary evidence is sparse, there seems good reason to think that the sheer weight of trees can increase the compaction, and hence density, of some soils. Day (1957) invoked such compaction to explain the abundance of root channels in soil that had become sparsely rooted, coherent, and massively structured in natural forests of Sitka spruce (Picea sitchensis (Bong.) Carr.). More recently Sands et al. (1979) have shown that soil under native scrub was consistently less compact than that under adjacent radiata pine (Pinus radiata D. Don) plantations on the same soil type, and that pine roots preferentially penetrated areas of lower soil strength. In a pot trial (Sands and Bowen 1978) increasing soil bulk density from 1.35 to 1.60 gm/cc halved the seedling weight of radiata pine. It is fortunate that the inevitable result of root death brought about by compaction is windthrow with consequent soil loosening and incorporation of organic matter. On soils liable to compaction (by no means all soils), the forester may have to simulate the effects of windthrow by plowing between rotations.

Reduction in forest cover is almost invariably followed by a rise in the soil water table. In a classic study Heilman (1966) showed that the increased wetness following breakup of canopies of black spruce (Picea mariana (Mill.) B.S.P.) in Alaska may lead to the development of a sphagnum moss layer; the resulting colder soils, and the decreased nitrogen status representing a marked reduction in site quality. Generally the problem is less severe, but in many wet regions clearfelling can be followed by problems of surplus soil water. Along the Atlantic coast of northern Europe, strip plowing is frequently used to provide turfs that lift newly planted or sown trees well above the saturated, anoxic zone (again, there is a tempting analogy with the mounds that result from catastrophic windblow). The forester, therefore, needs to adopt techniques that ensure that the desired species rapidly reestablishes an intercepting and transpiring canopy.

Some of the worst problems of compaction, wetness and soil puddling may result from the careless use of heavy machinery during felling and extraction, often necessitating plowing or ripping of skid sites or other severely affected areas as part of the site preparation for the next crop.

Chemical Considerations

The most obvious problems are those that may result from felling and extraction operations and subsequent site preparation, particularly if such operations lead to the physical relocation or destruction of the organic layer. Skidding, or the preparation of excessively neat windrows, may leave areas bare of top soil producing an unusual landscape and interesting problems for future harvesters, not to mention reduced productivity. Hopefully, silvicultural research can influence extraction techniques and machinery design. It must be emphasized at this point, however, that a particular constraint on such research is that extraction costs are such a high proportion of the cost of growing wood that no new technique, no matter how silviculturally or ecologically desirable, can be adopted unless it remains economically feasible within an industry dominated by the world market for timber.

Organic matter influences water holding capacity, soil density, cation retention characteristics, and nitrogen status, and for these reasons might seem to demand special protection. It also immobilizes many nutrient elements, prevents regeneration, and may represent a dangerous accumulation of fuel for wildfires. The arguments for and against slash burning or fuel-reduction burning have been well rehearsed and the factors involved widely reviewed. There is a loss of carbon and nitrogen and an accompanying release of ash elements, processes that are not of themselves harmful if (1) there is adequate nitrogen within the mineral horizons, (2) the accretion of nitrogen will subsequently be fairly rapid, and (3) cation exchange within the mineral soil will retain the ash elements. Except beneath very large piles of fuel, the mineral soil does not suffer much heating (review by Raison 1979), so colloidal organic matter and clays, with associated cation exchange surfaces, remain unaffected, and leaching losses, therefore, generally will not be severe (although surface erosion may be a problem). On fertile soils in Tasmania, Ellis et al. (1982) concluded that "in several respects the nutritional status of the soil is improved by present burning practices." But on the poor sandy soils of southeastern Australia, Farrell et al. (1981) concluded that conservation of organic matter is a key factor in the maintenance of productivity and cultural practices, such as burning and cultivation, that oxidize organic matter are to be

discouraged. There is no conflict between these two views for they refer to very different sites. It is futile to attempt to promulgate or proscribe any particular practice. Rather, the manager should be expected to assess the dangers and advantages for any unique set of site conditions.

A related problem that is attracting considerable attention is the loss of nutrients in harvested produce. Rennie (1955) drew attention to this drain and suggested that soil degradation and seriously reduced production may result. Ovington (1962) subsequently pointed out that the mean annual removal of most nutrient elements in tree trunks is largely balanced by the input in precipitation. Recent moves toward complete and whole-tree harvesting, however, have reopened the discussion. Although there is a range of estimates on the amounts of nutrients removed, the problem has been to assess the effect this might have on the nutrient status of the site. Miller et al. (1980) compared removals to the input in precipitation whereas Malkonen (1976) and Weetman and Webber (1972) related removals to total and exchangeable soil nutrients. All accept that the ideal would be to make the comparison with the rate at which nutrients enter the available pool within the soil. Certainly agricultural experience shows that simple comparison with amounts of exchangeable nutrients is very misleading (fig. 1).

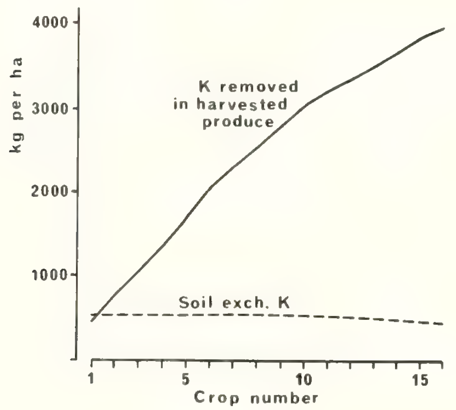

Figure 1.--Cumulative removal of potassium in harvested Napier grass (Pennisetum purpureum) and levels of ammonium acetate extractable potassium in the soil (from Ayers et al. 1947).

The length of a forest rotation precludes study of soil changes after successive cropping, but work by Lundgren (fig. 2) has shown a decline in the level of exchangeable nutrients during the early part of the rotation, while crowns are being constructed, followed by recharge thereafter. In this particular instance, however, the exchangeable potassium was not fully replaced because of extremely low total quantities of this nutrient in such old, highly-weathered soil. On these soils potassium fertilizers may need to be used to ensure the same productivity in the second rotation as that achieved in the first. Provided the appropriate minerals are present, rock and soil weathering generally seems to be adequate to recharge losses associated with harvesting removals (rock weathering is estimated to release an average of around 1 500 equivalents of electrolytes per hectare per year, Bache in press). Certainly, experience around the world (e.g., Farrell et al. 1981) suggests that yield in the second rotation will match that of the first, provided there are similar management intensities, even in fast-growing plantations of exotic species.

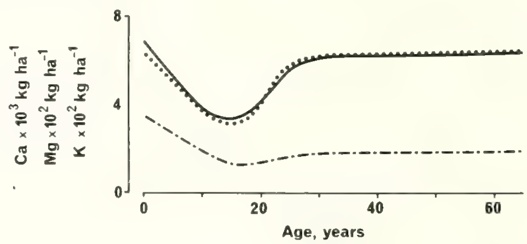

Figure 2.--Patterns of change in amounts of extractable calcium (————), magnesium (·······) and potassium (— - —) (in 0.1 M ammonium lactate plus 0.4 M acetic acid) in the top 10 cm of extremely potassium-poor lateritic soil beneath an age series of plantations of Cupressus lusitanica (Mill) in Tanzania. Redrawn from data of Lundgren (1978).

A further pathway of nutrient loss is the increased soil leaching that may follow removal of the forest cover, a result of reduced plant uptake, accelerated decomposition and stimulated production of nitrate to act as a mobile anion. Generally such losses are small (Cole 1981) and decline as the site is reclothed with vegetation.

Conclusion

With proper management there should be few problems in sustaining soil productivity, the key being to maintain a vegetation cover (even of weeds) both to prevent erosion and to retain nutrients. Soil compaction may necessitate plowing or subsoil ripping between rotations; but there are probably few sites where mineral weathering and atmospheric inputs will not compensate for losses in harvested produce, although these losses might represent a check in the rate of fertility buildup. Burning is a special case: The fertility of many sites may be unaffected, or even temporarily improved, by judicious burning, but on impoverished sandy soils, where much of the nutrient capital and many cation exchange sites are associated with the surface organic layers, burning is probably best avoided.

IMPROVEMENT OF SITE PRODUCTIVITY

In many areas of the world the most effective steps the forester can take are to change species and to control stocking: hence, the widescale adoption of plantation forestry. Such attempts to improve productivity through change in the genetic potential, however, may founder on limitations of the site unless measures are taken to improve or surmount these. It is important to distinguish between those actions that result in a genuine, long-term improvement in site potential and those that merely improve the growth of the present crop and will have to be repeated in subsequent rotations. Thus, the installation of a major drainage system, including cut-off drains, in wet areas is a permanent improvement, provided the drains are maintained. But the provision of planting ridges or turfs can only benefit the present crop. Such improvements, whether permanent or temporary, may only affect growth during the years prior to canopy closure.

Improvements to Crop Productivity

Defining productivity as yield to maximum mean annual increment, or height achieved at a certain age, is sensible in terms of management forecasting, but can hide very different growth histories. Three of the stands shown in figure 3 are, by age 25, showing essentially the same growth rates but very different productivities--a result of earlier variations in growth conditions.

Prior to canopy closure, tree growth is likely to be retarded as a result of weed competition, excess soil water or lack of nutrients. Suitable ameliorative measures taken at this stage may result in an appreciable reduction in the time until harvest. Once the canopy is closed, however, these problems largely disappear. By then competing weeds have been shaded out, high interception and transpiration have reduced the water input to the soil, and nutrient demands for growth have been reduced. The reduction in demand on soil nutrient capital once the canopy is completely formed is due to the establishment of fully charged cycles, both within the tree and through the litter layer. These reductions, as can be seen from the last lines of table 1, can be very dramatic.

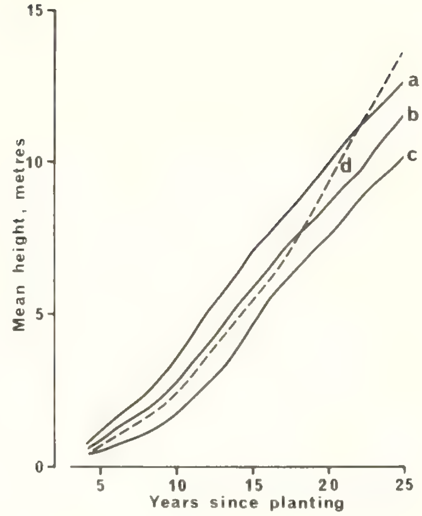

Figure 3.--Measured patterns of height development in stands of Sitka spruce (a) relatively unaffected by weeds or nutritional problems in youth, (b) troubled by early competition with Calluna vulgaris, (c) as in (b) but also phosphate deficient, and (d) a highly productive site but severe competition with Pteridium aquilinum during the establishment phase.

Miller (1981) discussed this change in nutrient cycling with age and pointed out that prior to canopy closure (termed Stage I) the trees, being very dependent on soil supplies of nutrients (see also fig. 2), may show growth responses to any of a wide range of fertilizer nutrients. After canopy closure, demands made on the soil capital are so low that supplies are rarely inadequate (Stage II) and fertilizer responses are therefore unlikely. An essential difference between Stages I and II, however, is the amount of nutrient required to form the foliage biomass. A reduction in foliage biomass during Stage II, such as results from thinning or insect attack, causes a partial reversion to Stage I, and the trees may again respond to the nutrient originally found to be deficient. So even in unresponsive Stage II, fertilizers can be used to accelerate recovery from thinning or any similar injury.

During Stage II, immobilization continues at a low rate within trees and, most important with respect to nitrogen, within the litter and humus layers (table 1). In northern regions with species that form a pronounced mor humus layer, this immobilization on sites with low nitrogen capital may lead to the gradual development of nitrogen deficiency conditions (Stage III). For some regions, such as much of the Douglas-fir zone of northwestern America, the nitrogen

Table 1--Comparison of rates of transfer and accumulation of nutrients modeled for a 10-year-old, 2-m-tall stand and a 40-year-old, 11-m-tall stand of Corsican pine (*Pinus nigra* var. *maritima* (Ait.) Melv.) (summarized from Miller, in press)

		10-year-old stand		40-year-old stand	
		N	K	N	K
		$kg\ ha^{-1}\ yr^{-1}$			
Net immobilization in growth	(A)	56	25	87	49
Release from trees	(B)	10	4	51	17
	(A + B)	66	29	138	66
Tree uptake	(C)	55	22	69	28
Retranslocation within tree	(D)	11	7	69	38
	(C + D)	66	29	138	66
Net immobilization in humus	(E)	3	(0.2)	12	1
Atmospheric input	(F)	5	6	5	10
Net change in tree stand	(C - B)	+45	+18	+18	+11
Net change in soil capital	(B + F - C)	-40	-12	-13	-1

capital of the site may be so low that Stage III-type nitrogen deficiency may develop soon after canopy closure. As the nitrogen capital increases, however, the delay before this occurs increases until, on better sites, it ceases to be a problem.

Improvements to Site Potential

For considerable investment in drains, stone removal, cultivation, and repeated fertilizer application, the arable farmer can create a site that, at least for 5 months during the summer, is vastly more productive than the site inherited. The forester cannot invest at this level nor get returns comparable to those in agriculture.

Fertilizers are seldom likely to have any measurable residual effect unless the amount applied is large in comparison to the nutrient capital of the site (Miller 1981) as may be the case in the application of many trace elements or in the disposal of large quantities of sewage sludge. The evidence available would even suggest that intensive cultivation has little advantage after the establishment phase of the existing crop, the exception here perhaps being soils in which cultivation destroys compacted or cemented layers that inhibit profile drainage.

Undoubtedly, hydrological schemes that improve regional drainage in areas characterized by swamps or peat bogs provide one of the most dramatic and permanent benefits to forest site productivity. The consequences for neighboring users of land and water can be constraining factors, but, where feasible, properly planned regional drainage schemes are very rewarding.

Also likely to result in permanent improvement are those techniques that enable the establishment of the first crop of trees on severely degraded sites, such as the spoil from mining or quarrying operations or the deposits left alongside rivers or by retreating glaciers. The limiting factor on such soils is almost invariably an inadequate supply of nitrogen as a consequence of their low organic matter content. Improvement under natural conditions is usually dependent on colonization by species, such as alder (*Alnus* spp.), capable of fixing atmospheric dinitrogen (e.g., Ugolini 1968). The time taken for such soils to reach a reasonable level of productivity can be reduced either by artificially establishing and managing an initial crop of nitrogen fixing species (e.g., Gadgil 1979) or, more rapidly, by applying nitrogen as fertilizer or in some stored form such as topsoil, sewage sludge or slurry (e.g., Bradshaw et al. 1982).

Conclusion

Productivity is most likely to be increased by those cultural techniques that reduce the time until canopy closure. Thereafter, the forest manager probably has little influence except in forests on low-nitrogen soils in northern regions where immobilization of nitrogen in mor humus can induce mid- or late-rotation nitrogen deficiency. To achieve rapid canopy closure, adequate drainage should be ensured, weed competition controlled (particularly if drought is a major limitation), and fertilizers used to correct nutrient deficiencies. These measures, however, are only of benefit to the existing crop. Indeed, it is difficult to find examples of long-term improvements in site potential except on soils where growth is severely constrained by

inadequate regional drainage, restricted profile drainage, or by very low quantities of organic matter in what is, almost by definition, a young soil. Although generally the fertilizer applications currently considered feasible do not significantly increase the nutrient capital, and therefore nutrient supplying ability, of a site, exceptions do occur, as when nitrogen deficient forest land is used for the disposal of sewage effluent.

POSTSCRIPT

To suggest that the forester has such limited control over site productivity should not be seen as a discouraging feature; rather it is encouraging to find that throughout most of the rotation, trees generally grow close to their climate-determined optimum rate without expensive inputs of energy or fertilizers. This is not to deny that there are occasions, particularly during the establishment phase, when such inputs are valuable and will give useful returns for suitably controlled investment. The problem remains to identify such situations, prescribe ameliorative treatments and, in particular, forecast returns. Research can best assist by increasing our understanding of the dynamic processes that link the soil and plants in forest ecosystems.

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METHODS FOR MAINTAINING AND IMPROVING FOREST PRODUCTIVITY IN NEW ZEALAND

G. M. Will and B. R. Manley

ABSTRACT: Because New Zealand forestry is almost totally dependent on exotic plantations (and predominantly one species--radiata pine), great emphasis is placed on maintaining and improving the productivity of pine forests. Work has focused on many aspects within the following topics: tree breeding to improve tree form and vigor; nursery and establishment practices to produce and establish seedlings that will not only survive but also grow vigorously from the start; site preparation to ensure seedlings are planted in an environment where they can realize their potential for rapid growth; weed control to prevent tree growth being restricted by competing vegetation; fertilization to correct severe soil nutrient deficiencies and stimulate growth on good sites; disease and pest control to maintain healthy stands; silvicultural practices to produce the desired end product with emphasis on the size, quality, and merchantability of logs; and harvesting practices to ensure that the potential gains from intensive management are realized.

Productivity is ultimately considered in financial terms. Though the total merchantable volume produced in a stand is important, it is the distribution of volume by size and quality that is of fundamental importance.

INTRODUCTION

New Zealand now depends on plantations of exotic softwoods for the supply of forest products for domestic consumption and an expanding export trade. New Zealand's economy traditionally has been based on exports of agricultural products but forestry is now contributing about 8 percent of overseas earnings. Substantial increases in the volume and value of wood exports are expected, particularly from the mid 1990's on, when stands planted in the current (post-1960) planting boom reach harvestable age.

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Exotic forest plantations currently total 900 000 hectares and the annual rate of new plantings is about 40 000 hectares. Radiata pine (Pinus radiata D. Don) is by far the most important species. It accounts for 85 percent of the established forest area and over 90 percent of current plantings.

Productivity is ultimately considered in financial terms. The importance of gross productivity (i.e., biomass and total merchantable volume) is not underestimated; however, it is not just the volume produced but also its quality (e.g., piece size, branching habit, straightness, etc.) that determines the value of a stand.

An exotic forest estate of 1.3 million hectares is the goal for New Zealand. Much of the land, however, that remains available for afforestation is relatively poor with regard to site quality and location. The onus is therefore on the forest manager to maximize productivity of existing forests. This is especially so in the short term because the uneven age-class distribution of New Zealand's exotic forests will cause difficulties in maintaining wood supplies to existing industry over the next decade.

The supply of wood will at least double by 2000 when it is expected that some 75 percent of forest products will be exported. The export market orientation of current plantings has placed greater emphasis on value per hectare and present net worth in assessing productivity. In fact, the New Zealand Forest Service, which owns and manages over 50 percent of the country's plantations, is required to achieve a real return of at least 10 percent on new forest investment.

There are many aspects to maintaining and improving productivity but, for the purposes of this paper, practices that have been successfully implemented are considered in eight areas:

1. Tree improvement
2. Nursery and establishment practices
3. Site preparation
4. Weed control
5. Fertilization
6. Disease and pest control
7. Silvicultural practices
8. Harvesting practices

It is important to stress that these categories are closely interrelated. The forest manager must take all facets into account if potential gains in productivity are to be realized.

TREE IMPROVEMENT

Radiata pine is the success story of New Zealand forestry. Many species have been evaluated but none can match radiata pine for productivity or the multipurpose qualities of its timber.

An intensive tree breeding program for radiata pine has been in progress for 30 years. Important selection criteria are stem quality (straightness and branching habit), growth rate, wood density, and disease resistance. The program was based initially on selection within commercial plantations (New Zealand Forest Service 1980).

At present, seed orchards supply about 70 percent of the seed used and by 1990 will supply all requirements. The seed now available from the first generation orchards is producing trees of better stem straightness than those from unselected seed, and with 5-10 percent faster diameter growth. Even better seed from progeny-tested orchards will become available in 1987 and is expected to give further improvements in stem quality as well as further gains in growth rate. An early economic advantage in using genetically improved stock is that initial stocking can be reduced (James 1979).

Provenance tests of native populations of radiata pine have recently been established on all important forest site-types in New Zealand to see if any grow faster than present New Zealand cultivated strains. Some earlier comparisons between native and cultivated radiata pine indicated that New Zealand strains were generally superior, so no spectacular improvements in growth are expected from introducing new provenances.

Research is being carried out on the micropropagation of trees. These techniques could offer potential for accelerating the tree breeding program by allowing the rapid production of large numbers of plantlets of selected clones suitable for use in future seed orchards and plantations (Smith and Aitken 1981).

NURSERY AND ESTABLISHMENT PRACTICE

Radiata pine is planted in New Zealand in the winter (May-August) using 1-year-old bare-rooted seedlings. The use of bare-rooted stock provides a cost-effective means of establishment.

Some years ago the success of planting was judged only in terms of seedling survival. Today emphasis is on survival plus the potential for the tree crop to grow fast in the first growing season after planting. Tree growth should be uniform within a stand so that all trees planted have the potential of being selected for the final crop. To this end all nursery practices--seed grading (i.e., uniform seed size), sowing times, depths and spacing, use of fertilizers, weed control, conditioning (undercutting, root wrenching, etc.) are designed to produce optimum, even-sized seedlings with maximum hardiness and "take-off" potential (Chavasse 1980). Conditioned seedlings with a low height:root collar diameter ratic (less than 60:1) and a compact, well-developed fibrous root system are produced.

Procedures for lifting seedlings from the nursery beds and handling during transport to planting sites are designed to avoid adverse effects on early growth. Planting techniques by hand or by machine are aimed at placing the seedling in the ground at a depth and with a root configuration that will allow seedlings to achieve full growth potential and develop into well-formed, stable, fast-growing trees. The range of nursery and establishment practices have recently been reported and discussed in FRI Symposium 22 (Chavasse 1981).

SITE PREPARATION

If a well-grown, genetically improved seedling is to realize its potential for rapid growth, it must be planted into suitable soil. Many soils available for forestry in New Zealand are chemically impoverished and physically ill-suited for

the rapid growth of tree roots. With compact clays and the pumice soils that have hard pans within 60-100 cm of the surface it is now routine practice to rip and/or bed to increase the rooting depth and form a soil having a bulk density and structure that will encourage penetration of roots.

Burning is a standard site preparation technique used to remove existing vegetation and logging slash. Many planting sites are subsequently prepared in a single operation: A winged ripper shatters the soil to a depth of 60 cm, discs form a cultivated bed over the rip, and a roller partially recompacts the soil. The rolling is to reduce the potential for erosion and increase the stability of the trees in wind.

Present machines cannot carry out this operation on first-rotation radiata pine sites being prepared for replanting because of stumps and logging debris. On these sites burning alone is the common method of site preparation. Where burning is not feasible, mechanical operations such as windrowing and V-blading are used.

WEED CONTROL

The results achieved by good nursery and establishment practice can be wasted if tree growth is restricted by competing vegetation. Common examples of competing vegetation are:

- grass competing for water,
- bracken or gorse physically overtopping trees and reducing photosynthesis, and
- root competition for nutrients (e.g., gorse competing for phosphate and boron).

The effect of weed competition on growth was considered by Watt and Tustin (1975). They pointed out the economic costs involved in the loss of productive area and the extension of rotation length caused by weeds.

Weed control starts before establishment. Where ripping and bedding are desirable and topography permits these operations, problems with weeds may be greatly reduced. Elsewhere other steps must be taken to control existing vegetation that will compete with the trees. These commonly involve the use of fire, which may be preceded by hand felling, machine crushing, or desiccation with herbicides. Gravity-rolling equipment and techniques have been researched and widely applied on new forest land in steep country. Crushing and burning followed by two, spaced, preplanting herbicide sprays (2,4,5-T or 2,4,5-T plus picloram) are being promoted for long-term gorse control. Asulam plus diesel oil, followed by fire is now commonly used for long-term bracken fern control. The most common herbicides for preplanting desiccation include 2,4,5-T, 2,4-D, paraquat, and sodium chlorate (Preest 1981). On grassy sites, preplanting spot or strip spraying is often used. Site preparation practices were reviewed in FRI Symposium No. 22 (Chavasse 1981).

Weed control is maintained after planting. Releasing from competing vegetation used to be done mainly by hand cutting. Today most areas are treated by spraying selective herbicides from ground vehicles or from the air. Atrazine, simazine, amitrole, hexazinone, 2,4,5-T, picloram, and asulam are in common use for post-planting selective weed control (Preest 1981). In some forests controlled grazing by animals has been an effective form of weed control.

On the North Island volcanic plateau, "frost flats" occur where frosts, particularly unseasonal ones during the growing season, can kill extensive areas of young trees. Weed control sufficient to maintain a bare soil surface reduces frost because it allows greater heat retention by the soil during the day and greater heat radiation during the night. By this means the severity of frosts can be reduced by up to 4° C, which is enough to make the difference between success and failure (Menzies and Chavasse 1983).

FERTILIZATION

Forests in New Zealand are fertilized both to ameliorate soil nutrient deficiencies and to stimulate growth on good sites. Fertilizers may be applied at the time of establishment (Ballard 1978) and later in the rotation, often after a thinning (Mead and Gadgil 1978). Fertilization at establishment is by spot applications by hand; subsequent applications of fertilizer are broadcast, mostly by aircraft. The recent introduction of spreading using a helicopter fitted with an electronic guidance system is an important advance. (For further details of fertilizer programs see a separate paper to this conference, Current Forest Fertilization Programs in New Zealand by G. M. Will.)

Nutrient deficiencies in radiata pine plantations in New Zealand have been described by Will (1978). Phosphorus deficiencies occur in a number of forests, particularly in the Auckland and Nelson regions, and are routinely treated by the application of fertilizer. Nitrogen is deficient in forests established on coastal sands. On stabilized sand dunes, lupins (Lupinus arboreus) have proved capable of fixing large quantities of N and substantially reducing fertilizer needs throughout the life of a tree crop. Trials are in progress with a wider range of legumes on a number of soils to evaluate their potential for improving the N status and increasing productivity.

The largest pine forests in New Zealand are on the generally nutrient-adequate pumice soils of the Volcanic Plateau. Growth responses of radiata pine to nitrogen fertilizer on these soils, however, have been demonstrated (Evans and Kemp 1980, Woollons and Will 1975). Two major private forestry companies in the region fertilize their forests as a matter of course: one company fertilizes stands after planting and

again after final thinning (age 8-12); the other company fertilizes only after thinning at age 13-14.

The interaction of fertilization and other management practices is important (Hunter 1980). The desirability of fertilizing at the time of thinning to gain the best growth response is an example. Similarly, weed control is required if trees are fertilized at establishment. Young trees on deficient soils are often better off without fertilizer in situations where the fertilizer stimulates competing vegetation. On skid sites, both ripping and fertilization are essential.

DISEASE AND PEST CONTROL

Implicit in the decision to continue with radiata pine as New Zealand's sole general purpose species is the assumption that its higher productivity can justify the spending of large sums of money to ensure vigorous and healthy growth. As with any monoculture, there is always the risk that a major disease or insect attack will affect productivity over large areas. Risks associated with monocultures have tended to be overstated (Bain 1981, Chou 1981).

In the late 1940's an introduced wood wasp, Sirex noctilio, caused high death rates of suppressed trees in many plantations. Stands had been predisposed to attack by drought and a lack of tending. Biological control by native and introduced parasites coupled with the removal of suppressed trees by thinning has resulted in Sirex damage now being insignificant (Nuttall 1980(a), 1980(b), Zondag and Nuttall 1977).

Dothistroma needle blight, caused by the fungus Dothistroma pini, was first recognized in New Zealand in 1964 and is now found in the majority of pine plantations in the country. Severity of attack is worst in areas of high rainfall, but radiata pine is generally only susceptible to the disease until age 15 years. It has been found that for young, fast-growing trees there is a direct relationship between foliage infection and loss of growth (van der Pas 1981); however, competition between trees with different infection levels influences increment lost by the crop as a whole, and further research is needed to quantify this.

In 1966 a Dothistroma Action Committee was formed to coordinate control action. This committee now plans and oversees the annual program of fungicide application. In July of each year the degree of needle blight infection in all forests is assessed and decisions made for the year's spray program. Copper oxychloride is applied at 2.08 kg Cu/ha. The recent adoption of nozzles that produce finer droplets has enabled the spray volume to be reduced from 50 L/ha to 20 L/ha (Kershaw et al. 1979).

This spray program, which over the last 5 years has varied from 6 000 to 120 000 ha, is considered to be effective in reducing disease inoculum levels and crop increment loss. Greater effectiveness of the aerial spraying program is the aim of current research.

With the exception of Dothistroma needle blight, radiata pine plantations in New Zealand are free from serious insect or disease problems. In an effort to maintain this situation, the New Zealand Forest Service has Forest Health Officers whose main function is the early detection of potential forest health problems. All exotic plantations are regularly inspected both from the ground and from the air. This, combined with the vigorous implementation of strict quarantine regulations, is considered important in maintaining forest health and productivity.

New Zealand has no native browsing mammals but many species have been introduced, and if numbers are allowed to build up, several could severely damage young plantations. Control measures are taken against deer, hare, possum, and wallaby.

SILVICULTURAL PRACTICES

A notable development in New Zealand forestry has been the increasing emphasis placed on measuring productivity in financial rather than physical terms. The evolution of silvicultural practices for radiata pine highlights this trend to value rather than volume becoming the yardstick for evaluating management prescriptions and practices.

Following comparatively small plantings in the early 1900's, large-scale afforestation took place in New Zealand between 1924 and 1936. These plantations were largely untended by design and because of a severe shortage of personnel during World War II. Management attitudes changed after the wood wasp epidemic in the late 1940's. Although the infestation was partially beneficial in that the weaker suppressed trees were killed by the insect, which resulted in a biological thinning from below, it made apparent the danger of allowing large areas of forest to become overstocked and stimulated the development of thinning regimes. Thinning was also favored to reduce rotation length.

Over the ensuing 25 years production (commercial) thinnings became the norm. A number of regimes were prescribed and though they generally included an early waste (noncommercial) thinning for sanitation purposes, they were aimed at maintaining merchantable volume production without excessive competitive mortality (Hinds 1962). A typical production thinning regime with pruning to 6 m (in two or three operations) and waste thinning to 600 stems per hectare by about age 10, might also prescribe one or two production thinnings to reduce the stocking to about 200 stems per hectare by age 20-25 years. Clearfelling was planned for age 35 to 40.

The importance of the quality of the product was recognized by Beekhuis and Will (1965). They suggested that productivity should be measured in terms of utilizable material rather than total organic matter produced. They proposed defining productivity in terms of the maximum volume of sawlogs of stated dimension and quality that could be obtained.

Management practices in the New Zealand Forest Service changed in the 1970's. Fenton and Sutton (1968) found that the production thinning of radiata pine had failed to increase realizable volumes or provide adequate intermediate returns to compensate for the loss of growth on the final crop trees. Consequently, they advocated a "direct" silvicultural regime; i.e., thinning directly to the final crop stocking without production thinning. Fenton et al. (1972) proposed waste thinning to a final crop stocking of 200 stems/ha by age 9 years with clearfelling at age 26 years. Variations of this heavy early thinning regime have been adopted for the production of sawlogs throughout New Zealand on most New Zealand Forest Service and many company plantations, but with final stockings ranging between 200 and 375 stems/ha (Williams 1983).

Lower initial stockings and pruning butt logs to about 6 m are integral parts of these heavy early thinning regimes. Pruning of the final crop component is generally carried out in three lifts. For example, a stand at Kaingaroa Forest might typically be low pruned to 2.2 m at age 5, medium pruned to 4.0 m at age 7, and high pruned to 6 m at age 9. Although pruning has been carried out in New Zealand for a considerable time (Hinds 1962), the rapid tree growth encouraged by current thinning regimes makes the timing of the operations critical to minimize the defect core. Knowles et al. (1984) have developed a method of predicting the diameter over the pruned branch stubs as a means of evaluating pruning strategies. Pruning schedules aim at obtaining a mean diameter-over-stubs of 16.5 cm. This results in a mean defect core diameter of about 22 cm (Park 1982).

Current sawlog silvicultural practices aim at a concentration, from an early age, of stand growth on a relatively few trees that have had their butt logs pruned. Thinning is heavy and early to ensure that the growth of the final crop trees is not restricted by competition from unpruned neighbors. The rationale is that, by possibly sacrificing some total standing volume, a crop of large, high-value trees can be produced in less than 30 years. A high proportion of this value is derived from the high-quality pruned butt logs which yield knot-free timber or clearwood. Fenton (1972) in comparing a direct sawlog regime with a production thinning regime observed that although both regimes had similar mean annual increments of sawn output, the direct regime produced a much higher yield of quality timber. The Radiata Pine Task Force (McGregor and Williams 1984) has developed a silvicultural stand model to ensure that a wide range of silvicultural options can be evaluated.

New Zealand forestry has moved toward directed silviculture, with silvicultural practices geared to the desired end product and emphasis placed on the size, quality, and merchantability of logs produced. Although physical productivity is important, it has been recognized that financial productivity and merchantability are the prime criteria in plantation forestry.

HARVESTING PRACTICES

Forest productivity cannot be considered apart from harvesting and processing because it is at these stages that wood is converted to dollars. Intensive management practices in New Zealand are producing stands of trees with considerable differences in value between large pruned butt logs and smaller knotty top logs. Emphasis is currently placed on research in harvesting, log segregation, and log allocation to ensure that the potential gains from this intensive management are realized.

A pilot study[1/] in "old crop," untended radiata pine found over 7 percent of merchantable volume was lost by breakage during felling. Directional felling studies have been carried out in managed stands on steep sites, and results indicate that felling trees across the slope rather than down it can reduce breakage (Murphy and Gaskin 1982). Because felling across slope resulted in a higher stump, however, it was found that value loss was minimized by felling trees downhill but parallel to avoid trees crossing (Murphy 1982).

Ferrow and McEwen[1/] also found that around 19 percent of potential value was lost by felling gangs being given suboptimal bucking strategies. This study showed that the crop type, log specifications, and market demand must be in harmony for maximum value to be attained. As a step toward achieving this goal, a preharvesting inventory method has been developed (Deadman and Goulding 1978) to enable the recoverable volume of a stand by log type to be assessed prior to clearfelling. The method involves cruising sample trees for size and quality (e.g., branches, straightness, forking, and taper). These inventory data are then analyzed using a dynamic optimization routine to simulate the cross-cutting of the trees into logs based on a defined set of log specifications and values. Widespread use has been made of this inventory system to determine the merchantable volume in stands and its distribution between various log classes based on size and quality, or the log-mix potential of a crop.

[1/] G. Ferrow and B. J. McEwen. Data on file at Forest Research Institute, Rotorua, New Zealand.

Attention is now being focused on refining log grades based on size and quality and on techniques of segregating and allocating logs. More efficient allocation of the resource directed at maximizing the value obtained from each tree should enhance financial productivity further.

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MAINTENANCE AND IMPROVEMENT OF FOREST PRODUCTIVITY IN AUSTRALIA

John Turner

ABSTRACT: The potential gains in productivity from a range of silvilcultural treatments have been discussed for various Australian forest types and sites. Because of their existing location and productivity, the main effort can be directed to the exotic conifer and native eucalypt plantations; however, these have been established on a wide range of sites, and to obtain the potential increases in productivity, further research is required to assess the treatment most compatible with the site. The treatments considered include site preparation prior to establishment, competition reduction, and fertilizer applications. Although increases in productivity can be obtained at all stages of the rotation, the largest gains are obtained at plantation establishment. Depending on the species and site, it can be expected that a site with a volume mean annual increment when untreated of 15 m^3 $ha^{-1}yr^{-1}$ over 30 years can be increased to 22-27 m^3 $ha^{-1}yr^{-1}$. Potential deleterious effects of management on long-term productivity are also discussed.

INTRODUCTION

The present and potential problems associated with maintenance and improvement of productivity over the range of forest sites in Australia are of growing concern as the forests become more intensively utilized. Although the wide range of forest types is of interest, the emphasis of this paper is both on the 700 000 ha of coniferous plantations that represent 1.7 percent of the 42 million ha of forest in Australia, and on the intensively treated, high-quality native forest (Class I eucalypt) (table 1). It is in these types of forests that the most deleterious impacts because of management activity may occur. They also have the greatest potential for yield increase, and considering the present low level of inputs for establishing and maintaining plantations and native stands, the potentials for productivity improvement are very high.

The assumption can be made that forest stand productivity will be maximized when optimum conditions exist. Suboptimal conditions will lead to reduced productivity, and treatments that result in altering conditions so they are nearer the optimum will increase productivity. Optimum conditions vary with changing environmental factors; thus, the matrix of conditions that defines the optimum will vary over a range of sites. Considering the wide range of forest conditions, optimal treatments for one area are probably not the same as those for others. The

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Table 1--Australian native forest areas classified according to forest types[1]

Forest type	Area
	ha
Rainforest	1 895 000
Eucalypt -	
Class I	2 703 000
Class II	14 236 000
Class III	12 198 000
Tropical eucalypt and paperbark	6 528 000
Cypress pine	4 372 000
Conifer plantations	700 000
Total	42 632 000

[1] Except for Cypress pine the native forests already or potentially have a mature height of 20 m+ (Australian Yearbook 1980).

stand requirements, and hence optimum conditions, can also be expected to vary with both the species and stage of stand development. Maintenance of productivity implies recognition of actual or potential declines in forest productivity; but, these declines are often difficult to define or estimate particularly where management practices change over the length of a rotation.

I have attempted to delineate the effects on productivity of various practices and future possible changes in these practices over a range of forest sites in Australia, and also review other impacts of some of these practices. In a review of the effects of management practices, the various aspects to be considered include (1) wood production, (2) wood properties, (3) disease potential, and (4) changes in plant diversity in native forests; however, the emphasis in this paper is on producitivity.

EXOTIC CONIFER PLANTATIONS

Although results from experimental work indicate the form of growth stimulation to be achieved, trials indicating potential maximum productivity have been established on only a few sites. There have been various studies on nutrient supply, weed control, alteration of soil physical conditions, and biological relationships; however, the major factor limiting growth--that is, moisture--has not been studied in detail in Australia.

Typically, *Pinus radiata* D. Don plantations in Australia are managed on a 30- to 40-year rotation, with two to four thinnings prior to clearfelling. Crown closure generally occurs before the stand is 10 years old with first thinning occurring between 12 and 16 years of age and subsequent thinnings taking place every 5 or 6 years. The southern pine plantations, concentrated in Queensland, are managed slightly differently but for the purpose of this paper may considered to be similar to the *P. radiata* plantations. In all cases, stimulation of rapid growth is essential in the initial years to reduce the time to the first thinning stage and obtain early returns from the financial investment. Although the actual growth gains will be detailed later, effective weed control at time of planting can gain 1 to 2 years in growth and even a small treatment of N-P fertilizer at establishment can gain at least 1 year and reduce the time to first thinning time from 15 years to 12-13 years. Plantation systems such as these with low levels of inputs lend themselves to gains in productivity at all stages in the rotation. The critical factor to consider on a site is the selection of optimum treatments for that site; not whether production increases can be realized.

Most research and most information on changes in productivity of Australian forests has concentrated on exotic conifer plantations, especially *P. radiata*. Substantial plantations exist in six of the seven Australian States (Australian Capital Territory has been pooled with New South Wales), and even though land ownership policies, planted species, climate, soils, and other factors vary considerably (Turner 1982), several major groupings of sites can be considered to allow generalizations to be made over the 750 000 ha of plantation (table 2). While these groupings have soil and other characteristics that are recognizable in the field, the most relevant aspect for classifying within the sites is the similarity of response of the stands to treatment.

Plantations on Deep Sands

Approximately 70 percent of the 150 000 ha of *P. radiata* plantation in southeastern region of South Australia and western Victoria is located on yellow podzolized sands of aeolian origin with the remainder on white podzolized dune sands. The nutrient status of these soils is low with less than 100 ppm total P and 0.07 percent N (table 3). Hopmans *et al.* (1979) found total phosphorus and nitrogen contents in the surface soil to be as low as 46 ppm P and 0.037 percent N respectively, and Woods (1976) reported surface soil total P as low as 20 ppm. Clay content is very low, and exchange sites tend to be related to the organic matter which may be less than 1.6 percent and often well below 1.0 percent. Prior to conversion to pine these sites would have carried open eucalypt woodland.

Gains in productivity were obtained in the first rotation of *P. radiata* on sands by applications of zinc and phosphorus fertilizers (Boardman 1974). Their low nutrient capital result in these soils being susceptible to declines in productivity because of nutrient removals in logging or losses in fire, but climatic conditions and a deep rooting zone allow for very good tree growth under an increased nutrient regime. It was on these sands that second rotation declines in productivity of *P. radiata* were initially noted and were a cause for concern in the 1960's (Bednall 1968, Keeves 1966, Mitchell 1970).

Table 2--Major characteristics of the various sites of exotic conifer plantations in Australia

Site name	General soil description	Predominant location	Rainfall (dominant pattern)	Major planted species
Deep sands	Podsolized in excess of 3 m deep	Southeast of South Australia, West Victoria	Winter	*P. radiata*
Humic and laterized sands	Shallow sands often with high organic matter	Coastal Queensland, Gippsland Victoria, Western Australia	Summer (Qld, W.A.)	Southern pines (Qld)
	Humic podzols or laterite podzolics	South Australia	Winter	*P. radiata* *P. pinaster*
Residual soils with low to moderate fertility	Podzolics developed from sediments and heavily weathered granites	New South Wales, Victoria, Tasmania	Summer or uniform or winter	*P. radiata*
Residual soils with high fertility	Red earths Kraznozems Red podzolics developed from granites and basalts	New South Wales, Victoria, Tasmania	Summer or uniform or winter	*P. radiata*

This led to work on many aspects of conifer productivity in the area. A wide range of soil factors was found to have changed between the beginning of the first and second rotations and to have significant effects on productivity. The changes included bulk density (Sands and Bowen 1978, Sands *et al.* 1979), nutrient status (Farrell *et al.* 1981, Woods 1980), weed competition (Farrell *et al.* 1981), and moisture availability (Squire *et al.* 1979). Declines in nutrient status were related, in part, to losses of organic matter by a variety of means from these sandy soils (Farrell *et al.* 1981).

To increase productivity, the maximum growth sequence was developed to supply nutrients on demand to the developing crop and, at the same time, provide minimum weed competition and the optimum conditions for root development (R. Boardman[1/]). In such a sandy situation adsorption sites for nutrients are limited, nutrients were applied initially on demand and as if in a hydroponic situation (table 4). The results have indicated probable growth gains (on the South Australian system) of at least two Australian system) of at least two site quality units (fig. 1) (Woods 1980). A reduction in competition, application of nutrients, and maintenance of organic matter result in increased growth such that productivity in the second rotation is in excess of that in the first (Squire *et al.* 1979). The results of the trials in Victoria have indicated that a mulching treatment consisting of unburned logging residues (Farrell *et al.* 1981) has also improved growth.

This may relate both to increased moisture availability because of the retention of the organic matter and to reduced nutrient losses with the absence of fires prior to stand establishment.

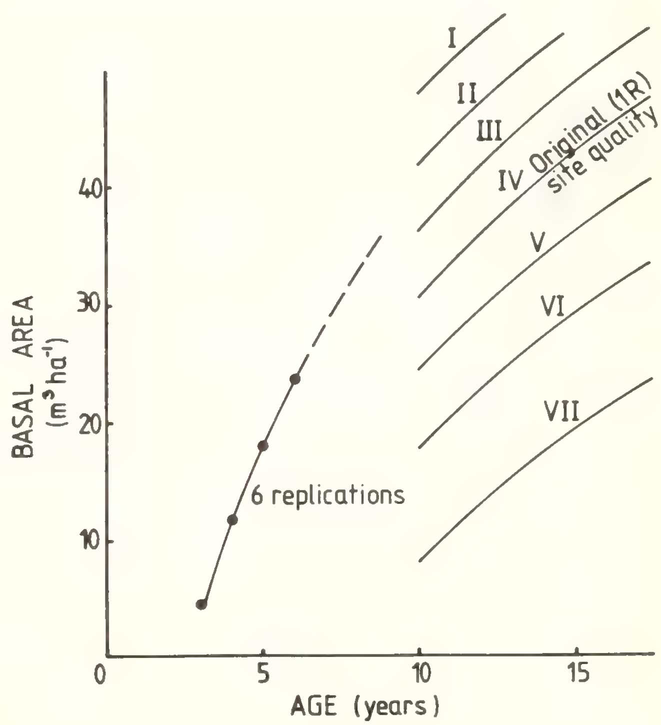

Figure 1.--Early basal area responses (m^2/ha) to maximum growth sequence treatments on a second rotation *P. radiata* site in South Australia (Woods 1976).

1/ Boardman, R. 1982. Woods and Forests Department, South Australia.

Table 3--Typical soil chemical characteristics of the major sites in Australian plantations

Site	Parent material	pH	O.M	N	Total P	Ca	Mg	K	Na	Al
						Exchangeable				
			- - - % - - -		ppm	- - - - - - - - - me% - - - - - - - - -				
Deep sands	Aeolian sands	5.48	1.6	0.07	95	3.85	1.01	0.06	1.45	0.01
Humic sand	Sands	4.65	2.6	0.04	25	0.21	0.19	0.05	0.04	0.96
Low fertility residual	Granite	4.78	4.3	0.08	60	0.07	0.32	0.61	0.13	4.29
Moderate fertility	Shale	4.46	6.3	-	210	0.58	0.44	0.52	0.09	5.76
High fertility residual	Basalt	5.51	15.7	0.36	1890	18.12	8.31	1.44	0.16	0.13

The sites are considered to be deficient in nitrogen, phosphorus, and potassium with secondary deficiencies of copper induced when growth is stimulated (Boardman 1974, Raupach and Hall 1974, Raupach and Clarke 1978, Woods 1976). It is clear that the sandy sites must be considered as finely balanced, that losses of organic matter and nutrients can lead to dramatic productivity losses, and high gains can be obtained from nutrient inputs. The experiments so far indicate that relatively short-term gains in productivity are obtained from fertilizer additions, but lack of soil adsorption sites may mean that longer term maintenance of productivity will require further modification of present techniques.

Plantations on Humic Sands

Approximately 40 000 ha of *P. radiata* plantations are located on humic sands on a series of sites in southeastern Victoria (Gippsland) and in Western Australia. In coastal Queensland 60 000 ha of southern pines have been established on these soils. Small plantations were initially established in New South Wales on similar poor sands on the assumption that if pines grew on would grow anywhere. These plantations were failures, however, and were destroyed by wildfire. Forest plantations on these humic sands, as with other land uses, have traditionally required amelioration with phosphatic fertilizers together with added calcium, potassium, copper, zinc, and boron to obtain acceptable productivity (Thompson and Hubble 1977). Although they are sandy, there is more profile differentiation and the soils are nutritionally poorer than the first group of soils (table 3). In 1973, when most fertilizer treatments of coniferous plantations were applied to poor-quality stands to obtain a crop (Turner 1982), more than 60 percent of the 13 800 ha treated in Australia were on the humic sands.

Apart from the nutritional limitations of these sands, soil mounding is frequently required to overcome drainage problems, and weeds can also be a major limitation to tree growth. Growth stimulation of trees by either mounding or the application of NPK fertilizers can lead to induced deficiencies in trace elements, particularly copper, but there are problems with the use of copper fertilizers because of the rapid fixation of this element in the soil organic matter.

Considering the extensive areas 8 of these types of sites, they will continue to be planted, but inputs will of necessity be high because they will require continual growth and nutritional monitoring to maintain long-term productivity.

Low to Moderate Fertility Residual Soils

Almost 300 000 ha (40 percent) of the total area planted to exotic conifers are located in soils originally derived from sedimentary rocks, granites, and extrusive parent materials in Australia. Such soils, which are

Table 4--Schedule of fertilizer applications for maximum growth sequence established in South Australia (R. Boardman, *pers. comm.*).

Time (months) after planting (P)	Soil type: P-fixing sands[1/] (especially lateritic podzolics)		Soil type: Non P-fixing sands	
	Fertilizer added			
Months	- - - - - - g/tree - - - - -			
P + 2	100		100[a2/]	
P + 10	140	-	110	-
P + 14	200 or	300	160	or 270[b]
P + 26	680		550[b]	or 360[c]
P + 38	640		520[b]	or 340[c]
P + 50	640		500[b]	or 340[c]

1/ Higher P levels due to P fixation.
2/ a, b, c indicate different formulations of

low to moderately fertile are found predominently in the States of New South Wales, Victoria, Tasmania and to a lesser extent in Western Australia. Rainfall is generally adequate with a distribution throughout the year that varies from winter-dominated, to uniform throughout the year, to summer-dominated depending on the location. This leads to some differences in growth patterns. The reasons these soils are available for forest plantations rather than agricultural purposes are topographical undesireability, low inherent fertility, or soil deterioration arising from excessive usage. There generally are expected to be one or more soil problems. Fertilizer programs on these sites, prior to the late 1970's, related to overcoming very obvious nutrient deficiencies, so the soils and stands have been the most intensively studied in terms of nutrition (Brockwell and Ludbrook 1962, Ellis *et al.* 1975, Flinn *et al.* 1979a, Gentle 1965, Gentle and Humphreys 1967, Lambert and Turner 1978, Turner 1982, Waring 1971, 1972).

Although considerable variation between the soil parent materials exists, generally they have an inherently low nutrient content and/or subsequent weathering has resulted in low nutrient status. The soils typically have low total phosphorus and/or available phosphorus, and have relatively low cations with the exchangeable concentrations in many cases being equivalent to the total (that is, virtually no reserve cation content, particularly calcium). Soil exchangeable aluminium can be quite high leading to higher phosphorus requirements by the tree (Humphreys and Truman 1964). Unlike the sandy soils, there are a large number of fixation sites so that phosphorus and other nutrients remain in the soil in various forms of availability. The soils physically, may be shallow, particularly in the case of some of the sandstone sites, and some of the weathered granites may be highly erodable. The potential increases in productivity from nutrient applications in conjunction with other treatments are quite high, the main limitation being the depth of soil leading to limited sustained water availability.

Early fertilizer experiments were established to assess superphosphate and rock phosphate as amendments to overcome fused needle disease (Ludbrook 1937), and these are still yielding results (Gentle *et al.* 1965, Humphreys 1964, Turner 1982, Waring 1971). Phosphorus is the primary nutrient limitation, as it was for the other two soil categories; but when phosphorus deficiency is overcome, responses to other nutrients such as nitrogen, can be readily obtained.

A sequence of trials located on one soil type can be used to indicate the extent of productivity gains that may be obtained. For this purpose a forest located in the Moss Vale District of New South Wales on yellow podzolic soils derived from very poor nutrient status Triassic sandstone (Hawkesbury sandstone) has been selected. Within the forest, a stand of *P. radiata* was clearcut in the mid 1940's and subsequently naturally regenerated; but growth stagnated. A trial was then established in the stand in 1951 and the

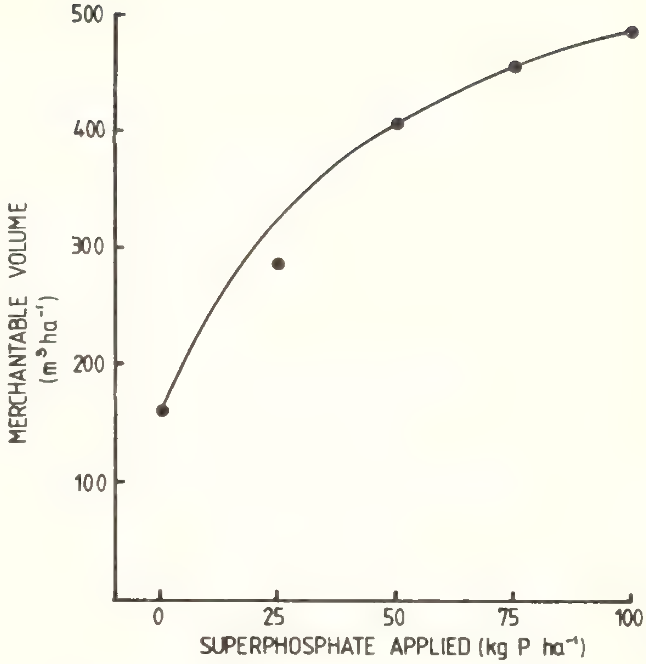

Figure 2.--Total merchantable volume (m^3/ha) after 30 years produced by *P. radiata* treated with various levels of phosphorus as superphosphate at Belanglo State Forest (Turner 1982).

results have shown that increasing levels of phosphorus resulted in increased growth (Turner 1982). Over the 30-yr rotation length, merchantable volume mean annual increment was increased from 5 $m^3\ ha^{-1}yr^{-1}$ in the untreated plots to 14.8 $m^3\ ha^{-1}yr^{-1}$ in the highest treatment of 100kg P/ha (fig. 2). Higher phosphorus levels applied to the same type of stand gave no further significant productivity increases (H. Waring *pers. comm.*[1/]); and it was concluded that without other forms of treatment, production stimulation levelled out beyond applications of 75 kg P/ha. Initially, because of the South Australian experience on sandy soils, some plots were treated with zinc spray but this had no effect. Analyses relating rainfall data to growth indicated that productivity was limited due to water deficits but that fertilization led to more efficient utilization of water (Turner 1982). Growth stimulation of *P. radiata* to watering was obtained on a comparable site near Canberra where there were treatments of irrigation, normal rainfall, and partial droughting carried out for 8 years (Waring 1971) (table 5). Irrigation resulted in a 75 percent increase in basal area while droughting gave a 70 percent reduction compared with the control. The weekly measurements showed that the peak demand was in summer and that basal area increment was correlated with soil moisture levels.

1/ Waring, H. 1979. Commonwealth Scientific and Industrial Research Organisation, Division of Forest Research, Canberra Australia.

Table 5--Mean annual basal area increment for *P. radiata* for a period of eight years of normal rainfall, irrigation and partial droughting[1].

Treatment	Mean basal area increment
	$m^2\ ha^{-1}\ yr^{-1}$
Droughting	1.23
Normal rainfall	4.29
Irrigation (1.3 cm water/week)	7.48

[1]The trees were 10 years of age at the commencement of the trial (Waring 1971).

Further gains in productivity on this site were obtained by eliminating weed competition, altering nutrient supply at establishment (Waring 1981) (table 6), and/or fertilization after thinning (Crane 1981),--factors that result in more efficient use of available moisture. The timing of fertilizer applications is critical for obtaining optimum responses (fig. 3) (Waring 1980). The highest gains from all forms of treatment will be obtained in the first 12 months after establishment.

The residual soils, unlike the sands, have strong fixation capacities for phosphorus and cations so that added fertilizer can be accounted for in the soil and effects on tree growth are maintained into the second rotation (table 7). In addition to increased soil phosphorus concentrations after fertilization, other changes such as increased forest floor weight and soil organic matter, decreased soil bulk density, and increased soil total calcium have been found (Turner 1982). With suitable plantation management, long term improvements in soil can be expected.

Although large gains in production are obtained from site preparation techniques such as plowing, blade plowing, and mounding at establishment,

Table 6--The effect of different establishment techniques on total volume (m^3/ha) at age 12 years for *P. radiata* at Belanglo State Forest (Waring 1981).

Site Preparation	No Herbicide: Nil	No Herbicide: Fertilized (NPK)	Herbicide: Nil	Herbicide: Fertilized (NPK)
	Total volume			
	m^3/ha			
Nil	44	206	142	311
Cultivated (after slash removal)	102	301	-	-
Slash Burnt	93	252	152	282

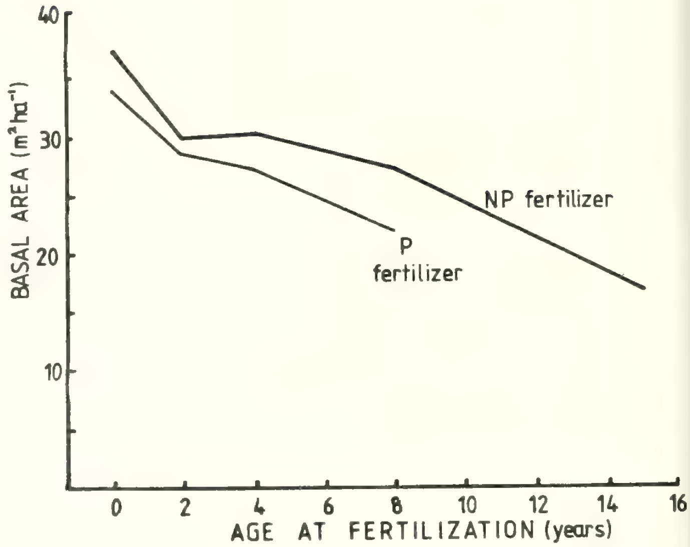

Figure 3.--Basal area at 18 years for *P. radiata* treated with P and N-P fertilizers at various years after planting.

later age fertilizing will also maintain and increase productivity. Variations in response are related to soil parent material and soil type; and to achieve optimum gains, the specific treatments must be matched to site and species (Ellis *et al.* 1975, Neilsen and Crane 1977, Turner and Holmes 1981, Turner and Lambert 1978).

Table 7--Total volume production (m^3/ha) at age 16 years in first and second rotations of a fertilizer trial at Penrose State Forest, New South Wales (Turner 1982)

	Fertilizer treatment[1]: Superphosphate	Rock phosphate	Control
	Volume		
	m^3/ha		
First rotation	130	135	43
Second rotation	176	161	67

[1] First rotation was natural regeneration, fertilized and destroyed by fire at age 17 years. Second rotation was then established with no added fertilizer.

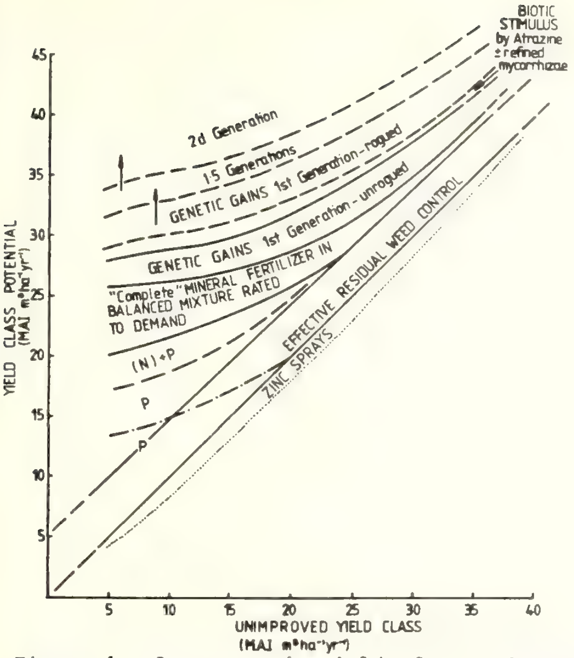

Figure 4.--Increases in yield of *P. radiata* in South Australia from different treatments over a range of sites (Boardman and Simpson 1981).

High-fertility Residual Soils

The high-fertility residual soils have a high nutritional status and are derived from granites, basic extrusives, and some sedimentary rocks. Although they form a continuum in productivity with the low- to moderate fertility soils, they have been dealt with separately because of the distinctive problems that arise. The soils contain high quantities of both available and total nutrients, particularly phosphorus and nitrogen. When nutritional problems arise, the trees generally have nutrient imbalances and induced deficiencies rather than absolute nutrient deficiencies. The nutrients most susceptible to induced problems are boron, sulphur, copper, and cations, and rather than resulting in greatly reduced productivity, there are usually growth disturbances such as boron tip dieback leading to multiple branching (Lambert and Turner 1978), copper-derived distortions (N. D. Turvey *pers. comm.*[1]), or induced fungal infection due to sulphur deficiency (Turner and Lambert 1978).

Originally many of these sites were improved pastures from which the native woodland had been removed, the area seeded with exotic grasses and legumes, fertilized with superphosphate, and then planted. The improved pasture sites are high in available nitrogen and are particularly prone to induced trace element deficiencies leading to stem deformities or foliar pathogen infection (Eldridge *et al.* 1981, Lambert and Turner 1977). Nitrogenous fertilizers applied without regard for the status of other nutrients will further exacerbate this situation (Lambert and Turner 1978).

[1] Turvey, N.D. 1981. Australian Paper Manufacturers, Traralgon, Victoria, Australia.

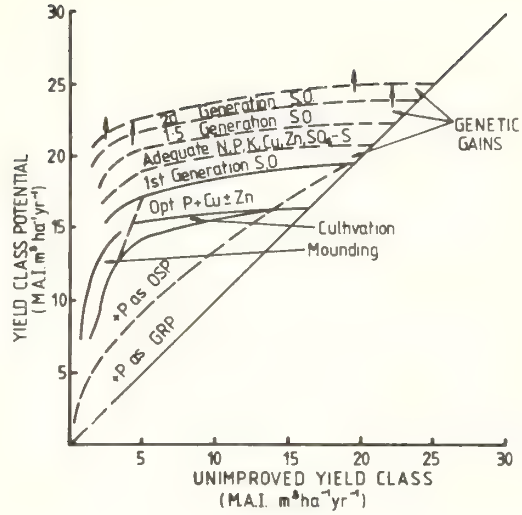

Figure 5.--Increases in yield of *P. elliottii* in Queensland from different cultural practices over a range of sites (Boardman and Simpson 1981).

At establishment, growth can be improved with physical amelioration of the soil, particularly blade plowing (deep ripping), on soils with compacted layers, weed control, N-P "starter" fertilizers (Carter 1981), and trace element amendments. The blade plowing needs to be carried out when the soils have a low moisture content to obtain a shattering effect. Soils that are poorly ripped can result in reduced survival and growth. Responses to nitrogen and N-P fertilizers have been obtained after various thinning treatments, and increases of 25 percent in periodic annual increment over a 5-year period appear to be typical. Although growth increases may not be as high at this stage of the plantation as those with establishment techniques, all the wood produced is high quality, there is a shorter pay back period in investment, and the possibility of increases in the production of specific products (for example, veneers).

INTERACTION OF TREATMENTS OVER A RANGE OF SITES

Over the range of different sites on which conifers have been established in Australia, increases in productivity of comparable magnitude have been found. The increases have been derived from similar types of treatments, that is, soil physical treatments, competition control, and nutrient additions considering the infertile soils; but the form of the treatment varies with soil type. An integration of a number of results over a wide range of sites has been attempted in a generalized diagram relating unimproved site class to the improved site class (Boardman and Simpson 1981). This was developed both for *P. radiata* in South Australia on deep sands (fig. 4), and for *P. elliottii* on humic sands (fig. 5). The full range of results for residual soils was developed for this review (fig. 6), and the three figures together indicate the variation

in inputs and responses in productivity. Examples show that for *P. radiata* on deep sands, the combination of fertilizers and weed control will increase mean annual volume increment from a base level of 15 $m^3\ ha^{-1}yr^{-1}$ to 27 $m^3\ ha^{-1}yr^{-1}$, while on residual soils it could be increased to 24 $m^3\ ha^{-1}yr^{-1}$. For *P. elliottii* on humic sands it will be increased to 22 $m^3\ ha^{-1}yr^{-1}$. Over a 30-year rotation, the above sequence of sites will have additional volumes of 360, 270 and 210 m^3/ha, respectively, compared with the base level establishment techniques. The main differences between sites result from differing physical treatments especially at the lower end of the productivity range, and varying trace element, nitrogen and phosphorus fertilizer requirements. The sands require continual inputs with less long-term fertilizer impact than the residual soils which generally have higher phosphorus fixing capacity.

Genetic gains were also included by Boardman and Simpson (1981), however they have not been estimated for residual soils as productivity increases have as yet not been reasonably demonstrated in these soil types. Demonstrable gains have been obtained with the southern pines (Nikles *et al.* 1978). Over a broad range of sites, changes in species may give significant production increases if used on sites where major problems occur with *P. radiata*.

Eucalyptus Forests

Studies aimed at increasing the productivity of native eucalypt forests have been concentrated in plantations (Cremer *et al.* 1978) as has been the case with conifers. Fertilizer experiments in a range of eucalypt species both on and off sites where the species grow naturally have shown that very large growth responses can be obtained predominantly with N-P fertilizers (Cromer 1971, McIntyre and Pryor 1974, Pryor and Clarke 1964). When N-P fertilizer treatments were applied at establishment, Cromer *et al.* (1975) increased aboveground biomass from 6.3 to 30.3 tonnes/ha in *E. globulus* at age 4 years. When fertilizers (especially nitrogen) were applied to later aged stands, production was found to increase (For. Dep. West. Aust. 1970, Higgs and Rudman 1973).

The experimental work carried out so far has shown that eucalypt forest productivity can be greatly increased, even though in practice the treatments tend to be limited to plantations and post-logging track revegetation using spot-applied fertilizer at low rates. The fertilizer treatments are predominatly aimed at giving sufficient early stimulus to outgrow the weed competition, but the potential for additional increases is present.

Apart from competitive vegetation, insects can have a large impact on production, and this has been demonstrated in a trial where regula insecticide treatments, in conjunction with herbicides and fertilizers, were used (R. Horne

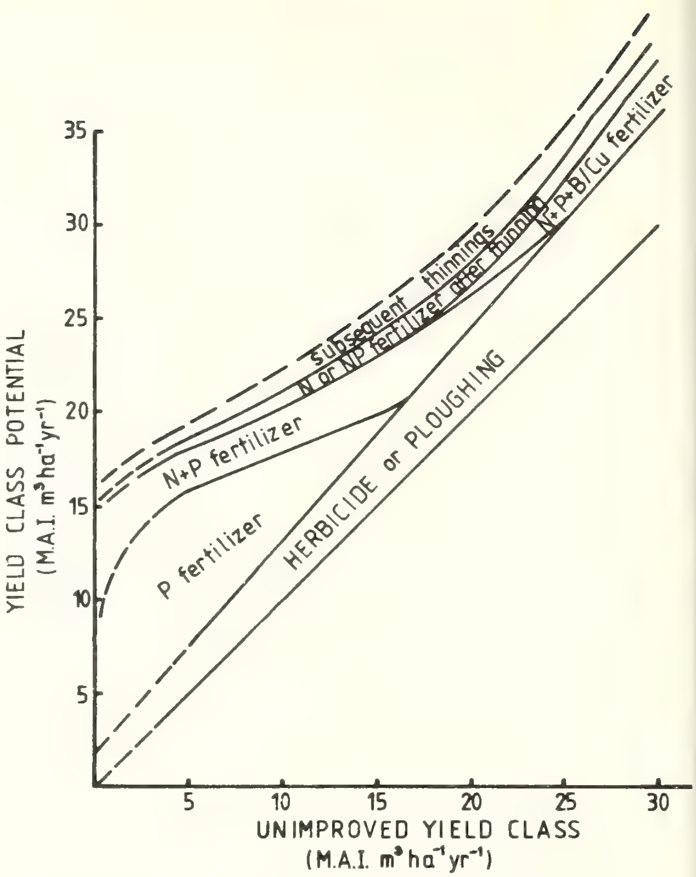

Figure 6.--Increase in yield of *P. radiata* from differing cultural practices over a range of residual soils

pers. comm.[1/]) (fig. 7). Considering the diversified nature of Australian native forests and the market situation, the potential for increases in production is very large; but the incentive for carrying out these treatments is not present.

IMPACTS OF MANAGEMENT ON FOREST SITE

Forest management practices can have various impacts on forest sites and on future productivity (Bevege 1981, Turner 1981). Over the full range of sites used for conifer plantations, the same factors will affect the sites but the specific impacts will be different. These factors include the effect of changing to coniferous species, losses of nutrients during establishment, removal of nutrients during logging, compaction and other soil physical changes, plus biological effects. The removal of nutrients in logging is relatively easy to determine; but the impact of this removal is very difficult to estimate, except on sites where nutrient status is already so low that fertilizers are being used

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1/ Horne, R. 1980. Forestry Commission of New South Wales, Australia.

to maintain productivity (Stone 1979, Turner 1981).

The actual process of conversion from eucalypt woodland conifers leads to decreases in soil organic matter and nitrogen over a range of sites. This is balanced by the accumulation of nitrogen in the aboveground biomass of the conifer as compared with adjacent eucalypts (Turner 1980). Establishment of plantations and the intensification of forest management lead to changes in the form and distribution of nutrients; but apart from simulations, no studies have shown that nutrient removals in logging or conversion to pine lead to productivity declines. This generally appears to be the case but one of the major impacts of plantation establishment is the effect of high-intensity burning, particularly on the sandy soils (Flinn *et al.* 1979b), leading to a serious loss of nitrogen and organic matter. During management of the stand, thinning will lead to compacted tracks, particularly on non-sandy soils; and this can be as much as 17 percent of the total area. On certain soils, particularly low-quality residual soils in the second rotation, there will be an overall reduction in productivity if these areas are not specifically treated.

The greater the intensity of management, the higher the intensity of logging and other treatments that can deleteriously affect soil properties. So while utilizing the sites, recognition of the problems is required (such as, reduction in wheeled traffic on waterlogged soils or additional nutrient removals) together with higher inputs at time of establishment and subsequent monitoring of sensitive areas throughout the rotation.

Virtually no work has been done on the impacts of management on eucalypt stands. Problem areas can be extrapolated from other forest types but substantiation is required. It has been found that as soil nutritional status changes in native forests, the species composition also changes (Turner *et al.* 1978, Turner and Kelly 1981). Intensive harvesting, such as that carried out in woodchip operations, may therefore lead to shifts in species composition and diversity rather than to declines in productivity.

CLASSIFICATION OF SITES

Management treatments that result in increased productivity can either be grouped as soil physical treatments, fertilization, or other cultural treatments such as weed control. Within each grouping there is a wide range of possible treatments. With fertilization there is a choice of formulation, rate, method of application, and timing together with considerations of the interactions with other practices. One obvious effect of this variation is a site-x-treatment interaction when a trial is established over a range of sites (Ellis *et al.* 1975, Flinn *et al.* 1979a). To optimize treatments and obtain the maximum effect from an input, each treatment needs to be correlated to site and stand condition.

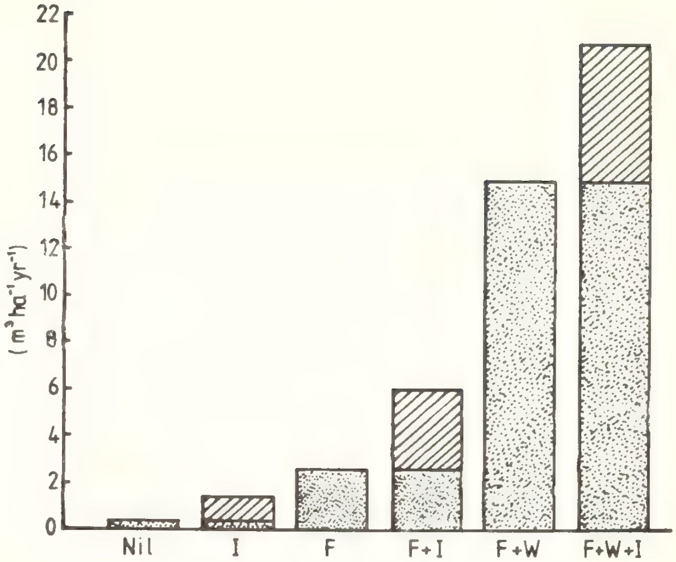

Figure 7.-- Effect of fertilizers (F), herbicides (W) and insecticides (I) on the 2-3 year volume increment of *E. grandis* on the north coast of New South Wales (R. Horne *pers. comm.* 1980. Forestry Commission of New South Wales, Australia).

Programs of site classification have been established and used to some benefit. In Queensland, site classification was used to allocate species to sites when plantations of southern pines were being established. In Victoria, Australian Paper Manufacturers used a site classification system to indicate the range of productivities of soil types and some indications of management alternatives have been given (Turvey 1980). A similar survey carried out in New South Wales forests gave comparable results (Turner and Holmes 1981). The effects of selecting the specific fertilizer for a site have been shown by Ellis *et al.* (1975).

CONCLUSIONS

The supply of timber from Australian forests is becoming more dependent upon the coniferous plantations. The future management of these forests will therefore be more intensive and will involve greater site preparation, weed control, and fertilizer usage. The potential gains from these practices are high. The sites where plantations are being established throughout Australia are highly variable and improved site classification procedures are required to optimize treatments to increase productivity and also to recognize sites where problems can be anticipated.

Forest management has been at a low intensity in both plantations and native forests in Australia. The gains in productivity can be high not only from site preparation and fertilization but potentially from species selection and tree breeding.

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METHODS FOR MAINTENANCE AND IMPROVEMENT OF FOREST PRODUCTIVITY IN NORTHWESTERN EUROPE

Bjorn Axelsson

ABSTRACT: A simple theory for forest productivity is presented based on nitrogen cycling and carbon dynamics. The theory is tested against results from a fertilization x irrigation study. The implications of the theory and field results to management practices designed to increase forest productivity are discussed.

INTRODUCTION

Evaluation of forest site productivity has so far been focused on the problem of establishing relations between *natural productivity* as a measure of *potential yield*, but almost nothing has been done to answer the question: What is the *real biotic potential* of the conifer species dominating the natural forests of the world today? A testable *theory* for forest productivity is needed. Considerable contributions have come from the International Biological Programs (IBP), but nevertheless central questions are still unanswered. One reason is that there has been too much comparative work and too few ecosystem experiments. It has been difficult or impossible to explore physiological laboratory data to develop a theory for the whole forest--a complex biological system comprising thousands of species. Looking back on the last decade, one might argue that the systems approach didn't help, partly because of misuse of the technique (Agren et al. 1980).

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In this article a simple theory for forest productivity is outlined and applied to an irrigation-fertilization experiment to evaluate whether the theory is economically acceptable under practical forestry conditions (Framlingshem experimental site). This experiment tests: (1) plant nutrition concepts developed under controlled conditions in the laboratory; (2) field irrigation and/or fertilization experiments in conifer stands; and (3) modeling analysis of complex dynamic systems. This particular Framlingshem experiment is also needed, along with other ongoing field nutrition experiments, to test parameter values and to generalize the theory. As the theory is closely related to nutrient cycling, evaluating not only total growth response to fertilizers but also discussing carbon partitioning within the whole forest stand are necessary. Knowledge of such changes in allocation patterns may be of significant importance for a cost-benefit evaluation of a silvicultural measure, but is also necessary as a scientific base for testing and predicting long-term effects on forest productivity.

EVALUATION OF SITE PRODUCTIVITY

Evaluating site productivity normally means making measurements of site and/or stand variables and expressing the result as a site

index or as mean annual increments at a fixed age or at culmination. Site index is height of a stand at a predetermined age, and is considered to be fairly independent of stand density. Height growth, however, is not necessarily a good index for total growth response to fertilizer application. Mean annual volume increment at its culmination is often used as a measure of site productivity and refers to an ideal stand, where growth is not affected by understocking. As production increases with time, the growth rate accelerates at first, inflects, and then declines. This means approaching a maximum value that is asymptotic and referred to as the carrying capacity of the system (in forestry equal to "yield class"). The common way to achieve the *potential yield of a site* is to combine mean annual increment figures with site index data. Normally, the influence of site on yield is sufficiently expressed through site index, but Assman (1959) introduced the concept of the "specific yield level." In practice a common experience is that many stands cannot reach the stocking level predicted by yield tables for fully stocked stands. But more important in this context is that the so-called potential yield can be increased by either raising the carrying capacity or by increasing the rate at which a given level is achieved. The difference between unrestrained growth and actual growth has been regarded as the environmental resistance and that is just the point; i.e., the potential yield referred to in forestry has very little to do with the *real biotic potential*. This has to do with a misconception in the use of the Mitscherlich equation, which assumes that *all other factors remain constant*. Evidently this is never the case in field experiments. In optimum nutrition experiments, Tamm (1968) applied nitrogen annually in an attempt to create different and relatively constant nutrient regimes. In this context the optimum nutrient requirement is an empirical result limited to the experimental conditions. But how close to or far from the biotic potential of Scots pine and Norway spruce will the final experimental results be?

Theory

Nitrogen is currently the principal limiting nutrient element both in Europe and elsewhere. It therefore seems reasonable to base productivity analysis on the nitrogen productivity concept as founded in the laboratory (Ingestad 1979) and in an analysis of field data (Agren 1983). According to the theory, the nitrogen cycling within the ecosystem is a major determinant of forest productivity and allows a simple description of forest stand biomass development. As shown in figure 1, stationary values for the needle biomass are linearly related to nitrogen flux within the system up to a saturation point. According to equation 1, however, the stationary values for the forest biomass as a function of the amount of nitrogen in stand biomass and soil litter describe a diminishing return (fig. 2):

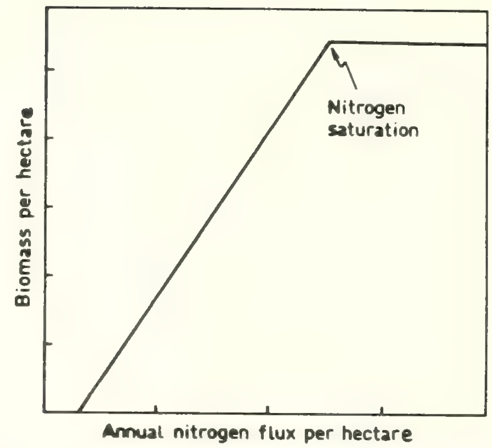

Figure 1.--Biomass production is linearly defined by the nitrogen flux in the ecosystem (after Ingestad et al. 1981).

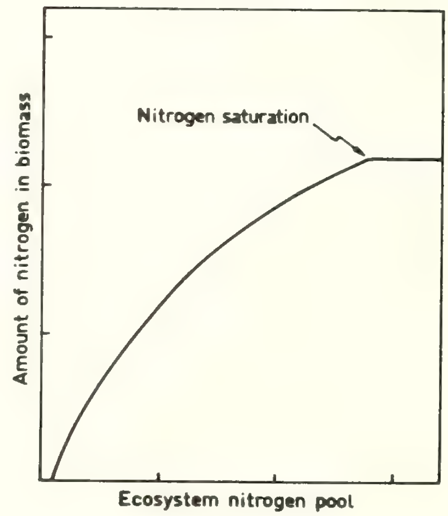

Figure 2.--Stationary values of the amount of nitrogen in the stand biomass at different values of the fast-circulating nitrogen pool (nitrogen in needle biomass and fast decomposing litter) (after Ingestad et al. 1981).

$$W = \frac{a-f/(N/W)}{b} \tag{1}$$

The parameters a and b determine the nitrogen productivity, f is needle death rate; N/W is the nitrogen concentration in the needle biomass; and W is the needle biomass (cf. Agren 1983, Axelsson 1982). The main feature of the model analysis is the carbon dynamics of the trees and the nitrogen dynamics of the trees and the soil (needle litter). This means that the nitrogen flow in the system consists of a mineralization rate and a fertilization rate.

Strategies for Field Experiments

Initial conditions at Framlingshem.--The Framlingshem experimental area is situated in middle Sweden at about 80 m above sea level; i.e., below the highest coastline after glaciation. The general topography of the region is rather flat, with height differences between the top of morainic eminences and the surrounding bogs of only 5 to 10 m. The moraine is stony and mostly covered with Scots pine often with an admixture of Norway spruce, particularly on the lower slopes. After windthrowing in 1954, scarification and sowing of pine and spruce produced a mixed young stand that was spaced when about 10 years old by almost total removal of the spruce trees. This produced a pine stand with an understory of suppressed spruce. Experimental plots (40 x 40 m) were established in 1981 in the 25-year-old pine stand of site index T24 (24 m, 100 years). About 10 hectares (90 percent of which is pine stands, the rest is spruce stands) are irrigated and fertilized using automatic equipment. The technique allows practical testing of both drop tubes and sprinklers. Daily irrigation and fertilization corresponding to 1 kg of nitrogen per day during the growing season will be compared to use of solid fertilizers.

To determine the initial stand characteristics, an inventory of the height and the basal areas of the plots was carried out during 1981. As an indirect estimate of the stand needle biomasses, the needle litterfall was studied by the aid of litter traps starting in August 1981. Although experimental layout was intended to create comparable conditions (i.e., approximately the same basal areas on different plots), fairly large differences were unavoidable. An example is Scots pine from block 1: The estimated needle biomasses and nitrogen concentrations in the 1-year-old needles as determined by chemical analysis for 10 experimental plots are illustrated in figure 3. First, the differences between plots are striking. Second, the overall agreement between predicted and measured needle biomasses demonstrates the strength of the nitrogen productivity concept. Third, the data also indicate the preference of making foliar diagnostic analysis during the growing season instead of the conventional samplings during autumn and winter (cf. Waring and Youngberg 1972). The conclusion is that nitrogen flux during the growing season explains, to a large extent, the variance in needle biomass although, as pointed out elsewhere (Axelsson 1982), too high soil moisture content can induce tree water stress, which in turn means lower production. Further evidence for the nitrogen productivity idea is a less-clear relationship between needle biomass and stem basal area, which indicates that carbon allocation is different from plot to plot depending on local environmental conditions (fig. 4).

Fertilization strategies.--It is possible to discuss three alternatives with regard to fertilization experimental design:

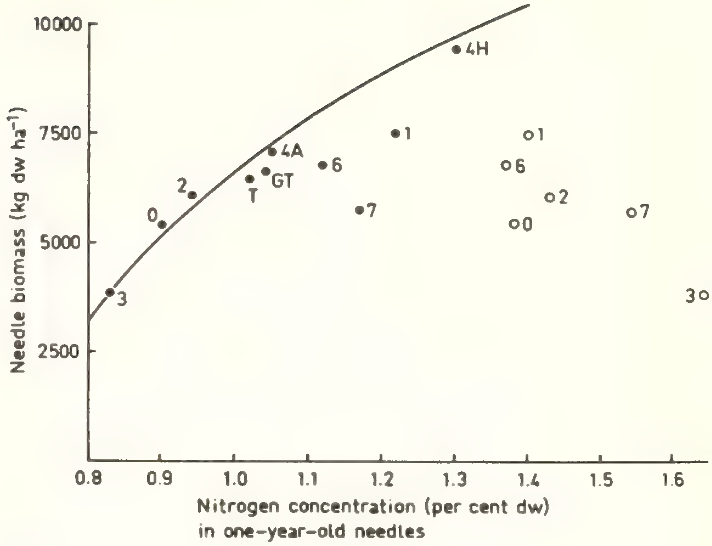

Figure 3.--Stationary needle biomass as a function of nitrogen concentration in the needles predicted by the aid of the nitrogen productivity concept (curvilinear relationship) and field data from Framlingshem experimental area, 1981. Foliar diagnosis July 14 (filled symbols) and April 7 (open symbols), 1981. Figures 0-7 refer to experimental plots.

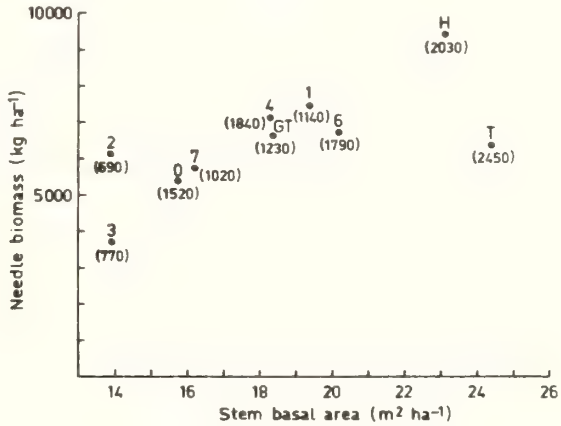

Figure 4.--Stem basal area needle biomass relationship at Framlingshem experimental area, 1981. Stocking density per hectare within parentheses. Figures 0-7 refer to experimental plots.

1. Conventional forestry practice; i.e., one large dose covering the needs of the stand for a 5-year period. Basic idea: the dose-response is curvilinear up to an application of about 450 kg of nitrogen per ha.

2. Maintain almost constant nitrogen regimes in needle biomass using annual applications. The annual dose depends on amount of biomass and soil fertility with the need checked by foliar diagnoses.

3. Fertilize daily in relation to the potential consumption rate of the whole ecosystem over

Table 1--Calculated fertilization rates for three different (initial soil fertility conditions) experimental plots at Framlingshem Experimental Area

Year	Needle biomass	Uptake from Fertilization Trees	Uptake from Fertilization Soil	Annual nitrogen dose[1/]
	- - - - - - - -	- - - - (kg ha^{-1})	- - - -	- - - - - - - -
PLOT 3				
1982	3750	31	15	205 (1st y saturation)
1982	3750	49	24	325 (1st y growth)
1983	6300	71	36	473
1984	10000	-	-	Saturated
1985	11000	-	-	total=1000
AVERAGE PLOT				
1982	6500	40	20	265 (1st y saturation)
1982	6500	72	36	480 (1st y growth)
1983	10250	-	-	Saturated total= 745
PLOT 4H				
1982	9500	27	14	183 (1st y saturation)
1982	9500	-	-	Saturated total= 183

1/ The aim is to maintain optimal (2 percent dry weight) nitrogen concentrations in the needles by the aid of annual applications.

the growing season. This means an application rate of approximately 1 kg of nitrogen per day with a smaller annual dose the first year and increased applications after 1 year according to need in the system.

References for the three alternatives are: (1) The Institute for Forest Improvement, Uppsala, Sweden (G. Moller); (2) Tamm and Aronsson (1983); and (3) Ingestad et al. 1981. The Swedish forest company, Korsnas-Marma AB, has the main responsibility for the experimental design and technical and practical evaluation.

Let us now apply the field data (cf fig. 3) on the nutrient flux density model (Ingestad et al. 1981) and choose three cases: plot 3, plot 4H and an average plot equal to mean site quality over all 10 plots in figure 3. It is then possible to estimate initial values of: (1) the needle biomass, (2) the amount of nitrogen in the needle biomass, and (3) the amount of nitrogen in the soil (only the part included in the model). Basic assumptions are that needle biomass is the maximum biomass as a function of site quality (stationary values) and that of a fertilizer application, 15 percent is taken up by the trees and 7.5 percent is taken by the soil subsystem.

The result of applying strategy (2) is shown in table 1. The data demonstrate that the most fertile plot (4H) needs only one dose of 200 kg of nitrogen to be saturated while the least fertile plot (3) needs 1 000 kg of nitrogen over a 3-year period. Alternative (2) in this context means annual applications to keep nitrogen concentration in the needle biomass constant at 2 percent dry weight.

Applying strategy (3) means that the application rate should match total uptake in the system but without increasing the risk of leakage. Reasonable fertilization rates are assumed to be about the same size as the mineralization rates within the system. Application of fertilization rates that are one, two, and three times as high as the mineralization rates are illustrated in figure 5. The process of saturation is strongly delayed if the fertilization rate is decreased. With a slow but perhaps reasonable rate this means 2, 9, and 16 years for the three plots to reach saturation, respectively, indicating large differences in initial fertility conditions. With conventional experimental design and statistical analysis such large initial fertility differences are a disadvantage, but it has been an advantage in the study reported here.

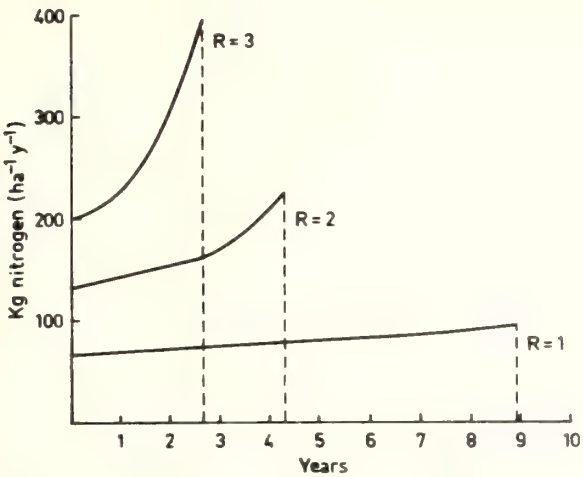

Figure 5.--Time to reach saturation of the "average pine stand" with fertilization rate (R) 1, 2, and 3 times as high as the mineralization rate. Initial needle biomass is 6 500 kg (dry weight) per hectare which means a total need of about 700 kg of nitrogen to reach saturation. The calculation is based on a daily liquid application rate of about 1 kg of nitrogen per hectare. Framlingshem experimental area, 1981.

Site Amelioration - Carbon Partitioning

One effect of the application of a growth-limiting nutrient is an increased leaf-area index, which leads to increased total production as long as incoming light is not fully used.

Measurements of photosynthesis on Scots pine show that a better nutrient status increases the photosynthetic rate, but only by 15 to 20 percent (cf. Linder and Axelsson 1983).

Only a few experiments have been reported in which differing levels of fertilizers were applied annually and changes in growth documented (Albrektson et al 1977, Axelsson 1981). From experiments in young stands of Scots pine and Norway spruce, a straight line relationship between aboveground production and the amounts of needles was found. In the spruce experiments, however, where most stands had dense canopies, the relation had become curvilinear because of self-shading (Tamm 1979). Recently a long-term experiment was reported in which irrigation, fertilization, and combined irrigation and fertilization were carried out in a young plantation of Scots pine (Aronsson and Elowson 1980). That study demonstrated that the amount of photosynthate allocated to root production is drastically reduced as the nutritional flux to roots increases (tables 2 and 3) (cf. Agren et al 1980b, Linder and Axelsson 1983). The same study showed that woody tissue production in relation to the amount of needles increases, with the exception of the coarse roots, with daily irrigation.

Changes in allocation pattern may vary with environmental conditions, but also with stand age. Recently, Grier et al. (1981) speculated that reduction in the supply of available nutrients might explain why older forests allocate more carbon to roots than do younger forests. Except for tree stability problems, carbon allocation might be related to water balance as illustrated in table 3, but may also be an effect of increased water stress in the tree with increasing age (size) (Axelsson 1983, Mattson-Djos 1982).

Silvicultural measures may also influence allocation. Comparing the data in figures 3 and 4 shows that although there is a fairly strong

Table 2--Annual biomass (dry weight) production in 1979 of a 20-year-old Scots pine stand at Ivantjarnsheden, mid-Sweden

Treatment[1]	Needles	Branches		Stems	Stumps	Roots		Total
		Current	Old			coarse (>2mm)	fine (<2mm)	
	($kg\ ha^{-1}\ yr^{-1}$)							
0	850	230	500	570	100	590	1800	4700
I	940	290	630	780	140	420	1800	5000
F	2550	860	1400	1580	280	2000	1800	10500
IF	2940	950	1590	2180	440	1300	1800	11240

1/ Treatments: 0 = control, I = daily irrigation, F = solid fertilization once a year, IF = daily liquid fertilization. Treatment period: late summer 1974-1979. Recalculated from Axelsson (1981).

Table 3--Relative distribution of annual biomass (dry weight) production in 1979 of a 20-year-old Scots pine stand, Ivantjarnsheden, mid-Sweden

Treatment[1/]	Needles	Branches Current	Branches Old	Stems	Stumps	Roots coarse (>2mm)	Roots fine (<2mm)	Total
	- - -	- - -	- - -	- - -	-(%)-	- - -	- - -	- - -
O	18.2	4.9	10.7	12.2	2.1	12.6	39.2	99.9
I	18.7	5.7	12.5	15.5	2.8	8.4	36.5	100.1
F	24.3	8.2	13.4	15.0	2.7	19.0	17.4	100.0
IF	26.2	8.5	14.2	19.4	3.9	11.6	16.3	100.1

1/ Treatments: O = control, I = daily irrigation, F = solid fertilization once a year, IF = daily liquid fertilization. Treatment period: late summer 1974-1979. Recalculated from Axelsson (1981).

relationship between needle biomass and stem basal area, a high stocking density may give an increased stem productivity and a low density may lead to decreased stem productivity.

CONCLUSION

Are sufficient thought and research being devoted to the consideration of the real productive potential of native forest tree species? The only way to know is to start field experiments in forest stands of different ages that are designed to provide a more fundamental understanding of the functional processes that produce and distribute organic matter and the effects of forest management on these processes. These experiments will have considerable importance for forestry practice. If a manager wants to maximize efficiency, strict control must be exercised when possible. Stand nutrition is a significant area to start with. The main contribution from scientists to the managers still is to tell them what they are doing.

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MAINTAINING AND IMPROVING THE PRODUCTIVITY OF TROPICAL AND SUBTROPICAL PLANTATIONS

Julian Evans

ABSTRACT: Plantations in the tropics are rapidly expanding. High productivity is reported for many first-rotation stands. No sizable declines in yield have yet been reported in second and later rotations but relatively few data are available. This must be watched carefully in the tropics, however, as high yields, short rotations, intensive harvesting systems, and use of monoculture may overstress fragile ecosystems.

Plantation improvement is mainly effected by better species/provenance selection and tree breeding. Soil cultivation is important for Eucalyptus. Use of fertilizer is not widespread, although correcting boron deficiency is important on many savanna/grassland sites. Disease and pest problems must be monitored on all large plantation projects.

INTRODUCTION

The theme of this symposium concerns forest site and continuous productivity, a theme which implies that we must never be complacent about current or future yields from forest land. In tropical and subtropical plantations, the problems of forest:site interaction are magnified owing to short rotations, high yields, fragile ecosystems, inherently infertile soils, severe climate, and, especially in developing countries, few opportunities for intervention on the scale or with the sophistication of modern technologies available to developed nations. Three aspects of tropical/subtropical plantation forestry need to be considered:

1. Characteristics of the tropical/subtropical plantation resource.

2. The concern for maintaining productivity.

3. Improving productivity - means and achievements.

TROPICAL/SUBTROPICAL PLANTATION RESOURCE

Extent

Estimates of plantation forest are notoriously inaccurate for many tropical countries, but table 1 is my estimate for 1980 (Evans 1982) which embraces countries lying between about 27 degrees north and south of the equator; i.e., excluding most of the Mediterranean climatic regions where _Pinus radiata_ grows so well. The figures in table 1 accord very well with those of Lanly and Clement (1979).

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Table 1--Areas of plantations in the tropics by continents

Region	1965	1980	1985 est.
	- - - (ha x 10^3) - - -		
Africa	1 423	2 595	3 643
Asia including southern China	4 420	10 323	15 862
Australia + Pacific Islands	70	262	384
Central America + Caribbean	218	510	759
South America	570	4 211	6 901
Estimated total area between 27°N. and S. of equator	6 701	17 901	27 549

Table 1 shows the rapid increase in plantations in the last few years and indeed planting in the present decade is at least double the rate of the 1970's and is likely to rise above the current level of 1.5 million hectares per year.

Species

Table 2 indicates the main species planted. The important point to note is the prominence of two genera of strongly light-demanding, pioneer species - Eucalyptus and Pinus. They account for over 70 percent of all current planting.

Purpose for Plantations

Table 3 indicates the main purposes for establishing plantations in the tropics.

Table 3--Purpose of plantations

Intended use	Region: Africa	Americas	Asia/Pacific	World
	- - - - - - % - - - - -			
Industrial	65	50	52	54
Fuelwood, including charcoal	9	29	4	18
Protection (erosion control, desertification)	6	10	36	17
Agro-forestry (shade, shelter, foliage)	1		5	2
Minor products	1	1		1
Small roundwood poles, posts	16	1	2	4
Other	2	9		4
				100

The data in table 3 are less accurate than those in tables 1 and 2 and are also more likely to change as interest in agro-forestry rises and the importance of growing fuelwood and planting to conserve soil increases.

Table 2--Species used in tropical forestry plantations

Genus/group	(order indicates relative importance)	%
Pinus	(patula, caribaea, elliottii, merkusii, kesiya, other)	33.7
Other conifer	(Araucaria cunninghamii, A. angustifolia, Cupressus lusitanica, other)	3.0
Eucalyptus	(grandis, camaldulensis, globulus[1], saligna, deglupta, tereticornis, robusta, citriodora, urophylla, other)	37.5
Tectona grandis	(teak)	14.2
Other hardwoods	(Acacia, Gmelina, Meliacaea, Terminalia, Albizzia, Triplochiton, other)	11.6
		100.0

This analysis does not include data from southern China where the main planted species are Cunninghamia lanceolata, Pinus mansonia, and P. yunnanensis.

1/ Only successful at high elevations mainly in Colombia, Ecuador, Ethiopia, India, and Peru.

Table 4--Average growth rates attained in some tropical plantations

Plantation development	Species	Mean annual increment	Rotation
		(m^3 ha^{-1} yr^{-1})	(yrs)
Usutu Forest, Swaziland	*Pinus patula*	19	15
Viphya Pulpwood Project, Malawi	*Pinus patula*	18	16
Fiji Pine Commission	*Pinus caribaea*	21	12-15
Jari Florestal, Brazil	*Pinus caribaea*	27	16
Scott Paper Co., Costa Rica	*Pinus caribaea*	40	8
Aracruz Florestal, Brazil	*Eucalyptus grandis*	35	7
Shiselweni Forestry, Swaziland	*Eucalyptus grandis*	18	10
PICOP, Philippines1/	*Albizzia falcataria*	28	10
Jari Florestal, Brazil	*Gmelina arborea*	35	10
CNGT, Papua New Guinea2/	*Araucaria* spp.	20	40
Seaqaqa Plantations, Fiji	*Swietenia macrophylla*	14	30

1/ Paper Industries Corporation of Philippines.

2/ Commonwealth New Guinea Timbers.

Growth Rates and Yields

Tropical plantations have a reputation for fast growth. This is true, but one must caution against applying figures based on single research plots in favored locations to what could be achieved for a whole forest. For eucalyptus and some other tropical broad-leaved species, average sustainable productivities above 50 m^3 per hectare per year and for pines above 35 m^3 per hectare per year over a whole forest are extremely rare. Table 4 gives mean yield data from 11 extensive plantation projects.

Even the mean yield figures in table 4 are impressive in relation to tree growth elsewhere (see table 5).

CONCERNS OVER MAINTAINING LONG-TERM PRODUCTIVITY

One of the main reasons for the increasing interest in forest plantations in the tropics is their rapid growth. In the moister tropics, yields are commonly three to seven times greater than either managed natural forest or most plantations in temperate regions. Almost all available growth data (table 4), however, come from first-rotation stands. Because the economic life of most industries dependent on plantation produce is much greater than the length of one rotation, and it is impractical to go on planting new areas of land to supply future needs, second,

Table 5--Growth rates of managed forest and plantations (modified from Wood 1975)

	Yield	Rotation
	(m^3 ha^{-1} yr^{-1})	(yrs)
Canada average	1.0	-
Siberia (Russia)	1-1.4	-
Sweden average	3.3	60-100
U.S. average	2.6	-
United Kingdom average (conifer)	10.0	40-65
New Zealand pines	18-30	20-40
South African pines	10-25	20-35
Subtropical eucalypts	5-30	8-25
Teak plantations	4-18	40-80
Tropical hardwood plantations	25-35	8-20
Tropical pines	15-45	8-30
Tropical eucalyptus	up to 60	7-20
Tropical high forest (managed)	0.5-7	-
Southeast Asia dipterocarp forest (managed)	up to 17	-

third, and fourth crops will need to be obtained from existing plantation sites. But will these later rotations yield as much wood as the first? Put another way, can ecosystems, relatively low yielding in wood such as rainforest and savanna, be turned permanently into highly productive forest plantations? Or is the very large initial gain only temporary?

This question of long-term productivity is important because it is the spectacular productivity of the first rotation that is encouraging development of many industrial plantations in the tropics. Unfortunately, no certain answer can be given about yields of later rotations since very few data are available. There are also many kinds of sites, many species, and many possibilities of change between rotations (genetic, climatic, etc.) that complicate the picture. Yet, because declining yields in the second rotation have been recorded in some instances, most notably with Pinus radiata in South Australia (Bednall 1968, Keeves 1966) it cannot be assumed that the performance of the first rotation will be maintained in later crops.

There are four possible factors that would lead to change in productivity between rotations: (1) climatic changes; (2) genetic differences; (3) site changes due to carrying out plantation forestry; and (4) biological and silvicultural differences.

These are considered separately followed by a consideration of what mensurational evidence is available for changes in productivity.

Climate

With short rotations and shifts in climatic patterns, especially in rainfall amounts in sub-humid and semiarid regions, variation in climate can significantly alter the yields from different rotations. This is most noticeable with a farmer's annual harvest, but can also affect forest crops (Evans 1978a). Indeed the growth of second rotation Pinus patula in the Usutu Forest, Swaziland, was significantly reduced owing to a succession of very dry and prolonged winters in the mid-1970's (Evans 1978b).

Genetic Differences Between Rotations

A change of species will clearly influence productivity but so too will change in seed origin or seed quality. Use of genetically superior seed in the second rotation could disguise evidence of a general decline in site fertility. This is particularly important in view of vigorous tree improvement programs with many plantation species; e.g., Pinus caribaea, teak, several eucalypts, and the use of more suitable provenances.

Site Changes Caused by Plantation Forestry

This subject has received most attention and it concerns the effects of one plantation crop on its successor. See Chijicke (1980) for a detailed account of the impact of fast-growing species on soils in the humid tropics. Changes may occur to physical, chemical, and biological characteristics of the site (Florence 1967) and are caused by three related influences. First, management-imposed factors may alter the site by ground preparation practices, addition of fertilizer, removals from the ecosystem in thinning and clearfelling, and by the way debris is disposed after harvesting. Second, harvesting trees can cause direct damage to a site. Dragging and skidding logs causes compaction, localized soil erosion, and unequal distribution of debris and organic matter over the site. Third, the plantation itself, and the litter it produces, will affect the site and soil in numerous ways, and it is these possible effects that have raised concern that some plantation monocultures may cause degradation of the site.

Site changes will be considered under four headings: effects on the chemistry, physics, and biology of the soil, and other factors.

Soil chemical properties.--Apart from adding fertilizer and the effects of such factors as soil cultivation or mulching, plantation forestry may affect soil chemical properties in two important ways. First, there is nutrient depletion from the soil into the trees as they grow and then from the ecosystem as they are harvested. Second, change may take place in the chemical status of the soil surface as the litter layer and organic matter becomes dominated by one species and the chemical composition and decay characteristics of the leaves and twigs become uniform.

Nutrient removal occurs as a direct result of plantation management because logs are taken from the site. Lundgren (1978) concluded that in managed Pinus patula plantations in Tanzania the mean annual removal of nutrients amounted to 40 kg ha^{-1} of nitrogen, 4 kg ha^{-1} of phosphorus, 23 kg ha^{-1} of potassium, 25 kg ha^{-1} of calcium and 6 kg ha^{-1} of magnesium. These figures are about one-third of those for maize (Sanchez 1976), but maize is usually grown on more fertile soil and some form of regular manuring is commonplace. The importance of these nutrient losses will depend on the total nutrients available in the soil; that is, how soon the soil will be exhausted, and whether the value of the nutrient-rich litter and debris left behind (leaves, twigs, lop and top) is lost to the site or becomes reincorporated.

The influence of litter on soil chemical status can be important because leaves of different species do not decay and release their nutrients at the same rate. In many tropical pine plantations, litter accumulation, breakdown, and incorporation are slow, and nutrients are only slowly recycled. In dense plantations, Pinus patula litter continues accumulating for many years and even under Pinus caribaea and P. elliottii, with lighter conditions and usually more varied ground flora, litter accumulates on

the forest floor for the first 10-18 years until trees are large pole size.

The buildup of large quantities of undecayed litter in plantations of broad-leaved species is much rarer. Even under teak and Gmelina, which usually suppress all other forms of vegetation, the large leaves readily decay. Similarly, the light crowns of most eucalypts lead to other ground flora species and relatively fast breakdown and decay of litter. Even the heavy fall of litter from leguminous trees does not lead to buildup because the high nitrogen content is attractive to numerous soil organisms.

Differences in litter type has two important consequences: (1) If net accumulation of litter occurs it effectively immobilizes nutrients. (2) Where a layer of litter of one species develops, the uniformity of dead organic matter results in (a) a single food type for decay organisms; (b) development of humus exclusively from one litter type; (c) uniformity in the chemical composition (ions and pH) of the water that percolates through to the soil.

The possibility of changes to the soil chemical status induced by a plantation has been demonstrated, but what has been observed? Most studies, including the examples below, have only compared conditions under plantations with those under the original vegetation (forest, savanna, etc.) rather than between different rotations of a plantation. Robinson (1967) found a drop in organic carbon and phosphorus under Cupressus lusitanica plantations compared with indigenous forest in Kenya. Cornforth (1970) found that on coarse-textured soils in Trinidad Pinus caribaea had led to depletion of nitrogen and most mineral nutrients as compared with natural forest. By contrast, Iyambo (1973) reported that Pinus caribaea on the Jos plateau (Nigeria) resulted in increased levels of phosphorus and some other nutrients compared with nearby grassland soils. Chijicke (1980) reported that on most sites where Gmelina has been planted total exchangeable basic nutrients in the topsoil show a definite increase over those in the original forest owing to more efficient nutrient cycling. Also, as might be expected, nitrogen accumulation has been reported under leguminous crops, especially when compared with grassland soils; e.g. Acacia mearnsii (Orchard and Darby 1956). Evidence from several studies suggests that the general acidifying effects of conifers on soils in temperate countries does not apply in the tropics (Lundgren 1978).

Plantation monoculture can be expected to change the soil nutrient status. The scale of change, its importance, and whether it will affect growth of later crops will depend on numerous factors but especially on inherent soil fertility and whether management practices tend to conserve or destroy nutrients accumulated in the litter layer and debris.

Soil physical properties.--Two main changes may arise from plantation forestry practice, change in soil moisture availability and change in bulk density and compaction. On some sites the presence of trees can lead to the water table being significantly lowered. There are several instances where eucalypts have been planted specifically on wet sites to dry them. Indeed, in Uganda, Eucalyptus robusta has been so successful in drying swampy ground that less flood-tolerant species, such as E. saligna can be grown.

It is difficult to quantify this effect on the growth of later rotations; but if the first plantation has consumed more moisture than received by the site in precipitation, soil moisture reserves will have been depleted. Many plantations established in the midwestern United States in the 1890's and 1900's thrived for a time but eventually died once moisture reserves were used up because precipitation was inadequate to sustain growth (Kramer and Kozlowski 1979).

Areas of compacted soil are very common following timber harvesting operations. Up to 35 percent of a site can be affected, and compacted soil is an important cause of poor growth. In Surinam, van der Weert and Lenselink (1973) found that clearance of natural forest using bulldozers greatly increased soil bulk density, and later work showed that growth of Cordia alliodora on the worst affected areas was only one-third of that where no compaction had occurred. A similar experience occurred with Gmelina arborea planted on old rain forest sites in the Amazon basin. Mechanical clearance of forest was abandoned for manual methods because there was much less damage to the soil.

Where successive rotations are grown, the necessary harvesting operations can lead to gradual deterioration of the soil by compacting it and altering bulk density. If rotations are short it may be important to plan harvesting carefully so the same tracks and loading areas are used and as much as possible of the site is protected from physical damage.

Soil biology.--Few studies have been done in the tropics comparing soil microflora and microfauna from under natural forest and plantations. Soil organisms play an essential role in tree nutrition, however, through litter breakdown, and nutrient and moisture uptake, and any significant alteration could be expected to alter growth.

Robinson (1971, 1973) reported changes in root mycorrhizal flora between rotations of Pinus patula and claimed that variation in growth of the second rotation was due to the presence or absence of the mychorrhizal association. Squire et al. (1979) have also observed changes in mycorrhizae between rotations of Pinus radiata.

Other factors.--It is impossible to list all the consequences of carrying out plantation forestry, but one other factor that has been widely

observed beneath teak, and to some extent under Gmelina arborea, is increased soil erosion. The problem is usually most serious when leaves and other litter are burned in the dry season.

In Trinidad an erosion loss of 152 t ha^{-1} of soil has been observed in teak plantations in years of high rainfall, compared with only 17 t from natural forest (Bell 1973). This problem of soil erosion under pure teak plantations, and possible soil hardening, has been extensively investigated in India (Griffith and Gupta 1948, Laurie and Griffith 1942) and appears to be a problem with the species on some kinds of sites.

Silvicultural and biological differences

Any change in silvicultural practices may alter the yield of one rotation compared with its predecessor.

One important and perhaps unrecognized biological factor, however, is the incidence of disease and pest damage. This can change markedly between rotations. Avoidance and control methods may improve and lead to higher yield, though conversely, later rotations of a species may suffer from more pests and diseases as these organisms become established in the forest and the period of initial relative freedom passes, especially for exotics (Gibson and Jones 1977). For example, in the Usutu Forest, Swaziland, some insects (e.g., Hylastes spp.) are now effectively controlled, but new ones, such as aphids, have also appeared that were not present during most of the first rotation. Greig[1/] has reported an increasing incidence of Fomes annosus in P. caribaea stands in Jamaica as thinning and regeneration operations become more widespread.

Evidence of Changes in Productivity in Successive Rotations

The reasons why plantation yields may change with each rotation have been briefly considered. The important question is whether or not yields actually decline (or improve) from one rotation to the next. Has the growing of one plantation crop influenced (adversely) the growth of its successor? Few data are available. Few second or later rotation crops exist. It is difficult to compare two crops 20 or more years apart, and, particularly in the past, management has concentrated on sustaining yield from a forest as a whole rather than monitoring yields over a long period from individual sites.

Evidence of changes in long-term productivity has been reviewed by Evans (1976, 1978b, 1980) and is considered most conveniently by the main plantation genera-pines, eucalypts, teak, and other species.

[1/]Greig, B. J. W. 1981. Fomes annosus and other diseases in the pine plantations of Jamaica. Unpublished report, U.K. Overseas Development Administration.

Pines.--Most interest in long-term productivity concerns pines, mainly because of reports in the 1960's of serious (25-33 percent) drops in yield of second-rotation Pinus radiata in nearly all regenerated stands in the Mt. Gambier area of South Australia (Bednall 1968, Keeves 1966) and on some sites in the Nelson area of New Zealand (Muir 1970, Whyte 1973). This evidence of decline, however, though Kio (1976) assumed it would apply to tropical plantations, is probably not wholly relevant to the tropics and subtropics. P. radiata is a warm temperate species, and many second-rotation stands elsewhere are equally or more productive than the first, which is even true of some third-rotation ones in South Australia (Boardman 1978).

Studies of long-term productivity of tropical pines have been limited by the small areas of second-rotation stands of measurable size. Nearly all plantations of the most widely planted pine in the lowlands, P. caribaea, are first rotation.

P. elliottii has long been planted in the cooler tropics and subtropics and several second-rotation stands exist. There are no reports of growth decline, and data from an experiment in Queensland, Australia, comparing two rotations show the second crop to be marginally superior so far. In this experiment the second rotation of P. elliottii was grown from seed collected from the same parent trees as for the first-rotation crop 30 years before. Not only is there no evidence of productivity decline but soil analyses indicate no changes (Queensland Department of Forestry 1979).

Long-term productivity of P. patula plantations has received more attention than other pines, both mensurationally (Evans 1975, 1978b) and in terms of changing soil and ecological conditions (Lundgren 1978, Robinson 1967). Studies of second-rotation performance in the Usutu Forest, Swaziland, have revealed no marked reduction in productivity because of site degrade after two complete rotations, though second-rotation stands showing better and poorer growth were found (Evans 1978b). In the comparative work in Swaziland, seed genetic quality changed little between rotations but, as noted, climatic differences, especially in rainfall amounts and distribution, differed considerably.

There are no reports of declining growth in second- or third-rotation crops in South Africa (Schutz 1982).

Eucalypts.--Comparing rotations of eucalypts differs from pines in that most stands in the tropics have been established for fuelwood or lowgrade roundwood and are managed for several coppice rotations before replanting. Thus the productivity question has two forms: the relative growth of successive coppice crops and the longer term comparison of yield of successive seedling (replanted) crops including their coppice yields.

Coppice yields generally decline after the first coppice crop mainly because of stump mortality. There is no firm evidence that regular coppicing itself leads to a long-term decline in site productivity, and in some countries coppice has been carried out continuously for over 100 years (Jacobs 1981). This conclusion also summarizes what is known about successive seedling crops of eucalypts, and there are no reports of long-term declines in productivity because of site degrade. Seedling regeneration as opposed to coppice does allow genetic changes of the crop providing opportunity for improvement from new species, provenances, or using superior seed. Under certain circumstances declining yield can occur from genetic degrade.

Where eucalypts are planted as exotics, often in trial collections or arboreta, there is much opportunity for interspecific hybridizing which would not occur naturally in Australia. The example in Brazil of E. 'alba' is well known and the continuing use of 'Brazilian' seed, collected from stands of hybrids up until the mid-1960's, resulted in successively poorer plantations reflecting the effects of deleterious segregation. At Aracruz Florestal, in Espirito Santo, for example, the early plantings of E. 'alba', yielded a mean annual increment of about 22 $m^3ha^{-1}yr^{-1}$. By using E. urophylla from Timor or E. grandis from the northerly Atherton provenance in Queensland, Australia, yields are expected to average about 35 $m^3ha^{-1}yr^{-1}$ an 80 percent improvement in later plantings and the second rotation.

Teak.--Reduced growth in the second rotation of pure teak plantations in India and Java (Indonesia) led to research into what was termed "the pure teak problem" (Griffith and Gupta 1948, Laurie and Griffith 1942). More recent research has not generally confirmed this problem, and no sign of deterioration in site quality has been found with replanted teak at Kerala. As mentioned, there is concern that excessive soil erosion under teak will, however, lower yield in second and later rotations.

Other species.--For acacia, Lewis (1967) quotes a report that up to eight rotations of A. mearnsii have been harvested from the same site without apparent growth decline; but rotations are short and, because the crop is leguminous, some benefit may derive from their nitrogen fixing ability. Few other studies of long-term productivity have been reported though second-rotation investigations are beginning in Auraucaria cunninghamii stands in Queensland, Australia (Bevege and Ryan 1981).

IMPROVING PRODUCTIVITY - MEANS AND ACHIEVEMENTS

The main tools available to foresters for improving productivity in the tropics are the same as elsewhere, though factors such as short rotations and the early reproductive maturation of trees do allow improvements to be effected and assessed on a shorter time scale. Offsetting this, however, is the generally greater fragility of many tropical ecosystems, which can sustain disturbance less well than temperate ones. Thus, the need for improvements and care in implementing them may be all the more important.

Crop Improvement

Provenance testing and tree breeding figure prominently in tropical plantation silviculture. There are substantial gains to be made and breeding can achieve results in a short time span. To indicate the extent of the work, I quote from Palmberg (1981):

> Based on the priority lists drawn up by the FAO Panel of experts on forest gene resources, exploration and collection followed by the establishment of centrally coordinated international provenance trials have to date been accomplished for 14 tropical and 6 Mediterranean or sub-tropical species, viz. Araucaria angustifolia, A. cunninghamii, A. hunsteinii, Cedrela odorata, Eucalyptus camaldulensis, E. microtheca, Gmelina arborea, Pinus caribaea, P. kesiya, P. merkusii, P. patula, P. oocarpa, P. pseudostrobus, Tectona grandis, Pinus halepensis, P. brutia, P. eldarica, Abies cephalonica, Pinus radiata, P. muricata.
>
> Progress is being made on the exploration, collection and distribution of a number of other species and genera, e.g. Aucoumea spp., Terminalia spp., Acacia aneura, A. auriculiformis, A. mangium, Cordia alliodora, Eucalyptus deglupta, E. urophylla, E. globulus, E. delegatensis and Cedrela spp. (supplementary collections); plans have also been made for the collection/evaluation of some additional species such as Pinus strobus var. chiapensis, P. canariensis, Prosopis spp. and Leucaena leucocephala. Through the activities of IUFRO, good progress has been made in the collection, distribution and evaluation of temperate species, especially North American conifers and Populus spp. Detailed biological studies are being conducted on a number of potentially important tropical species, e.g. Agathis spp. and Triplochiton spp.

For an example of this work, table 6 illustrates the results of trials with provenances and varieties of Pinus caribaea in Queensland.

One development of particular interest, notably with eucalypts, is vegetative propagation of phenotypically superior individuals and promising hybrids. Both in Brazil, e.g. at Aracruz Florestal, and in the Congo the development of clonal plantations of eucalypts for pulp production is far advanced and is being vigorously implemented.

All the improvement work described above assumes a good matching of species and site. Indeed this

in itself is a tool for improvement involving careful site survey and study of the local climate. The guide by Webb, Wood and Smith (1980) is an excellent starting point. Increasingly there is interest in the matter of genotype:site interaction. In the data shown in table 6 the most productive provenance of Pinus caribaea in the Byfield experiment is not proving to be the best a little further south in Queensland on wetter, less sandy sites. This possibility of carefully matching genotypic variation with site variation to obtain the very best performance is almost limitless, and only now is work beginning in this field.

Site Improvement

The benefits from cultural inputs have been found to vary enormously.

Fertilizers.--Although use of nitrogen and phosphorus, well known in temperate forestry, has been locally important in the tropics (e.g., the need to apply phosphate to pines in Nigerian savannas), it is the micronutrient boron (B) that has been most universally important. On many sites addition of boron has been essential to prevent multiple leaders in pines and dieback in eucalypts; indeed in parts of Africa its use has quite altered plantation prospects.

In South Africa the benefits of fertilizing eucalypts are well documented, e.g. Schultz (1976).

Cultivation and weed control.--Eucalypts and pines though perhaps equally light-demanding as pioneers, show remarkably different tolerances to competing vegetation. Complete surface cultivation, done primarily to suppress all grass growth, leads to a doubling of height growth in eucalypts growing on the South African veld compared with just fertilizing and hand weeding (Schonau et al. 1981). By contrast most tropical pines can grow through grass but succumb on old rainforest sites unless they are cleaned and weeded regularly of herbaceous weeds, vines, and climbers.

As elsewhere in the world, cultivation and fertilization can make the difference between crop success and failure on particularly poor sites (see table 7).

Damage Avoidance

Avoiding site deterioration.--Mention has already been made of this subject but it is one that needs stressing as a negative "benefit." Care not to damage the site at the end of the rotation when extracting trees or burning off lop and top is important to avoid degrade. Retention of litter and logging residues after clearfelling is operationally feasible, and, because of their nutrition and moisture conservation benefits, may greatly assist in maintenance of productivity especially on sandy sites (Farrell et al. 1981).

Crop protection.--Protection of forest crops is

Table 6--Performance at 9.1 years of different varieties and provenances of Pinus caribaea in Byfield Forest in the coastal lowlands of Queensland

			Performance					
Batch No.	Variety	Provenance	Mean dbh	Predom. height	Volume	Wind throw	Stem straightness[1]	Foxtailing[2]
			(cm)	(m)	(m^3ha^{-1})	(%)		(%)
B22	bahamensis	Grand Bahamas	15.8	14.3	90	0	2.56	0
B19	caribaea	Cuba	16.0	13.0	81	1	2.60	0
B17	hondurensis	Mountain Pine Ridge, Belize	18.5	16.4	111	3	2.10	7
	hondurensis	Dona Maria, Guatemala	18.7	16.4	120	7	1.99	1
	hondurensis	Cristina Qu, Guatemala	17.5	15.1	90	13	2.01	7
	hondurensis	Poptun, Guatemala	17.7	15.5	96	0	2.11	4

1/Individual tree assessment, 1 = poorest form, 6 = best form.
2/The habit of producing continuous leader growth without side branches.

Table 7--The effects of site preparation and fertilizer application on growth of Pinus caribaea var. hondurensis on an infertile groundwater podzol in Byfield Forest, Queensland, Australia.

Treatment		Assessment at 12 years			
Cultivation	Fertilizer	Predominant height	Mean diameter breast height	Basal area	Total volume
		(m)	(cm)	(m^2ha^{-1})	(m^3ha^{-1})
Nil	nil	2.6	-	-	-
Nil	P, N, Cu	11.0	15.7	18.0	64.3
Nil	P, N, Cu, Zn, Mo	12.1	16.9	21.7	79.2
Mounding1/	P, N, Cu	15.7	18.7	28.0	121.7
Mounding	P, N, Cu, Zn, Mo	16.8	19.6	30.2	139.3
Mounding and ripping2/	P, N, Cu	16.7	20.0	31.8	146.0
Mounding and ripping	P, N, Cu, Zn, Mo	17.5	20.5	33.7	161.8

1/Mounding was done using the tilted edge of a bulldozer blade, and done over the ripped line when the two cultivation treatments were combined.

2/Ripping was done with a single tine with a wing attached to a depth of 60 cm along planting lines.

as important a part of maintaining productivity as the other cultural practices described. There is no need here to go into the matter of fire protection, disease control, monitoring the effects of hail damage, and windthrow, but all of these play an important part in tropical plantations. What needs to be stressed is that the relative freedom from disease or insect problems of most tropical plantations is likely to be only transitory. In general, monoculture plantations of exotic species have a relative freedom for the first rotation only; increasingly we can expect diseases and pests to appear. It is incumbent then that full monitoring of these problems forms an integral part of all major plantation forestry programs. This is already being done, for example, on the large Viphya Plateau project in Malawi where monitoring insect populations in the extensive Pinus patula stands is carried on continuously throughout the year.

CONCLUSION

Plantation forestry in the tropics has much promise of creating a sizable new forestry resource. A careful watch must be maintained, however, on the effects of plantation forestry on the ecosystem and whether by growing extensive areas of monoculture, sites may be overstressed. There is no evidence yet of a serious long-term productivity problem. The consequences of forest destruction in the past, however, show that most tropical ecosystems are fragile. Compared with temperate ones, the tropical ecosystems appear more prone to destruction and irreversible damage; there is no room for complacency regarding plantation forestry in the tropics.

Finally, nothing has been directly said about protective afforestation, village wood lot schemes, social forestry, agro-forestry, and related community-orientated developments. The theme of this symposium is forest site and continuous productivity but all our labors must be to the end of improving the lot of people. Nowhere else in the world can this be improved so significantly than by the judicious planting of trees in and around the numerous villages of the Third World. When it is remembered that 90 percent of all trees cut down in developing countries are burned as firewood for cooking and heating, our responsibility is clear--to ensure that woodlands are maintained, expanded, and improved to meet this fundamental need of human existence.

ACKNOWLEDGMENTS

The data presented in tables 1-7 come from Evans (1982).

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USE OF BALANCED MINERAL FERTILIZERS TO PRODUCE ACCEPTABLE GROWTH RATES IN *PINUS RADIATA* ON MARGINAL SITES IN SOUTH AUSTRALIA

R. Boardman

ABSTRACT: Sites afforested with Pinus in South Australia range in fertility from marginal status for agronomic land uses to highly impoverished. The native forest flora has adapted to this marginal nutrition by use of "fine-root strategy" complemented by symbiotic root associations and decreased shoot:root biomass ratios. The high level of success in producing closed forest by native species of Eucalyptus and Acacia has often failed to reflect the paucity of nutrient supplies.

Mixtures of fertilizers have been found to produce significant gains in productivity when applied in stepped annual dosages related to target growth uptake over the first 5 years of the rotation over a wide range of sites. Large responses have been found to these mixtures applied in conjunction with thinning operations later in the rotation.

The way in which the results affect continuity of productivity have been shown in terms of site potential as indicated yield class. They show that fertilizing in this manner takes advantage of the characteristics of the pine and its root system.

INTRODUCTION

Australian soils are among the most naturally impoverished in the world. The last glaciation on the mainland occurred in Permian times. Since the separation of Australia from Antarctica began in Cretaceous times, large areas have been subject to inundation by the sea to depths up to 200 m above present sea level. Land above 200 m has served as refuge for forest. The uplands, with climate able to support forest, have been subjected to continuous weathering and the soils to almost continuous leaching for over 100 million years. Most of the forest genera found today have been present for over 40 million years.

In South Australia, the land above 200-m elevation able to carry forest has been small in area. It is also isolated from other uplands in Australia. In addition to adapting to the gradual impoverishment of soils, the native forest species have also been subjected to wide variations in aridity and rainfall distribution, both of a strongly stressful nature. There are

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acid soils on the uplands. Often, in contrast, lowland areas available for colonization and radiation during normal or low sea levels have been mantled with limestone and soils of neutral to alkaline reaction distributed by aeolian agencies. As a consequence, the native flora has had to adapt both to gradual and short-term stresses in nutritional factors or perish. These are some of the factors that have decimated genetic resources as well as provoked special strategies to cope. The native forest flora of South Australia, in general, has adopted sclerophylly and has developed a fine-root strategy allied with microbial symbionts to cope with the low-nutrient situation (Bowen 1981) and the current mediterranean climate. The limited supplies of native timber were decimated within 30 years of European colonization, which began in the 1830s. Strong public reaction to dwindling supplies caused the state government to embark on an afforestation program to provide a substantial proportion of the colony's timber needs. Today, commercial forestry in South Australia is based upon even-aged pine plantations composed almost entirely of Pinus radiata D. Don. There are plantations of Pinus pinaster, Pinus muricata, Pinus halepensis/brutia, and Pinus canariensis which are minor in extent. All these pine species, selected from over 100 tree species screened over 60 years ago, are well adapted to the local mediterranean climate. Among them, Pinus radiata is prominent. It has naturally high vigor, good form, and has desirable wood properties.

To satisfy the nutrient requirements, these pine species have adopted a "thick-root" strategy and an associated ectomycorrhizal symbiosis in their environment. Bowen (1981) has called this the "magnolioid type" in contrast to the "graminoid" or fine-root type widely adopted in the native forest flora and typical of the grass family. The magnolioid root system of pines is markedly different. It has a root intensity many times lower and less root-hair development. It is found in soils of moderate fertility where the flushes of nutrients, associated with the seasonal rainfall pattern, are readily intercepted, stored, and transferred within the tree to sustain growth during periods with warm air and soil temperatures. Theodorou and Bowen (1970) have shown by the growth rate response of the pine on marginal soils that fungal species forming mycorrhiza vary considerably in their effectiveness.

The natural occurrence of native forests often misled agriculturists, and subsequently foresters, as to the remarkably impoverished nature of the soils. Their suitability for crop plants that evolved on more fertile soils of the northern hemisphere has often been grossly overestimated. A large part of the land afforested with pine in South Australia has been acquired from farms that have failed or have been unable to compete economically.

THE PRODUCTIVITY OF *PINUS RADIATA* IN SOUTH AUSTRALIA

It is a benefit to an international audience to express productivity in real terms rather than in relative ones such as "site quality." In South Australia, there is a wide range of productivity associated with different sites; and it ranges in yield class (YC) from YC 7 to YC 42 (where YC is expressed as m^3 ha^{-1} yr^{-1} at the age of culmination of mean annual increment (m.a.i.) - this is becoming a convention commonly used). The average for all the state-owned plantations is about YC 22.

Most of the low yield classes are subject to limitation in growth by the availability of phosphate. Large areas in the southeast region of the state where soils are derived from aeolian sand deposits (sorted and resorted dunes) are podzolic in nature and subject to an overall primary deficiency of the trace element zinc. In the upland forest areas, phosphate deficiency is common on relict lateritic podzolic soils and podzolic gravelly sandy loams derived from bedrock. In contrast to the aeolian sand soils of the southeast, these soils have a high phosphate fixation capacity. Agricultural experience on soils of both the major areas afforested has been that attempts to alleviate low phosphate and nitrogen status have often revealed, or induced, a wide variety of trace element deficiencies. These factors, in spite of the lower "demands" of tree species, are potentially hazards in attempts to improve the health or the productivity of pine plantations.

Productivity and Maintenance of the Yield

To observe whether or not a stand is in fact continuing at expected rates of change with time, as established by standards (usually production yield tables), the dynamic changes in current or periodic annual increment need to be indexed. There have been strong incentives in South Australia's pine plantation forestry to establish a simple indexing system to arbitrate on the question of sustaining growth rates. The application of silviculturally significant growth amelioration practices, such as cultivation, weed control, and nutritional fertilizing, have all modified productivity to a degree in the short term, but the significance of these changes in the long term is also important. Current or periodic annual increments are among the most sensitive measurements of changed growing conditions, but they are too immediate and too large in magnitude in the short term to be of use in long-term projections.

When the continuity aspect of productivity across a wide range of sites and fertility conditions is being considered, having criteria that emphasize this is useful. One that has been useful is yield class and, in particular, the potential yield class that can be expected of a stand if current trends continue. This has led to the

estimation of "indicated yield class" (iYC). If the iYC derived from growth data does not change with stand age through m.a.i. culmination, then, by definition, the growth is being sustained; there is "continuity in productivity." If the iYC increases or declines with increases in stand age, then productivity is being enhanced (the species potential to grow is being more fully realized) or depressed (the "environmental resistance" is being increased). The way the iYC index has been derived in South Australia provides a way to make diagrams in which a sustained trend is shown as a horizontal line parallel to the abscissa (time). The basic estimations are derived from basal area per hectare (B) and predominant height (H)[1/] parameters because these are useful estimators of stand stem volume (V = a+b(BH)). It has been found that the correlations between B and V, and H and V can vary with particular types of site, but their product (BH) is complementary and without a significant effect on V across sites.

The trends with age of both basal area per hectare and stand predominant height expressed for all site quality classes in the yield tables (Lewis et al. 1976) form a family described by the Chapman-Richards (C-R) equation. The theoretical asymptotic values for each site class have been designated as index values. The basal area index (Ig) is the asymptotic value of total basal area production for age, and the height index (Ih) is a similar value of height for age. The maintenance of a given index value at successive ages shows that basic trends, as shown in yield tables, are followed (Boardman and Archer 1980).

Yield class in volume under bark can be estimated from the product of Ig and Ih. In the case of Pinus radiata in South Australia:

Indicated YC (total stand, stem volume, ib) = $0.005\ (Ig \cdot Ih) + 0.7544$ (1)

NUTRITIONALLY BASED GROWTH RATE DISORDERS

The first major breakthrough in solving growth disorders occurred in the late 1930s with the discovery that deficiency of the trace element zinc was the cause of top dieback. Research into the provision of ortho-superphosphate (OSP) followed this discovery and it provided a remedy for rapid decline in growth rate on lateritic podzolic soils. This latter work commenced in the mid-1940s and proceeded in strongly leached dune and sand soils in the southeast later in the decade in conjunction with zinc additions. Initial attempts were made in stands already failing, but by 1948 applications of OSP at the time of planting were being investigated. There were a few trials in which nitrogen and trace elements (as a mixture) were also included.

These trials have been assessed for over 25 years and have shown some significant information on the nature of phosphate metabolism and continuity in productivity. First, the long-term effect of very low availability of phosphate on decline in growth rate from many control plots in both the major kinds of phosphate impoverished soil (strongly fixing and non-fixing) follows a similar pattern. After an initial period of apparently adequate phosphate for small trees in the first 2 to 4 years, a decline may set in that follows a simple power relationship with time when compared with the C-R model of the yield tables. In the empirical data this decline is always manifested in plantation trees by 6 years after establishment. It is strongly revealed by diameter growth (assessed in basal area production):

$$Ig = aA^{-b} \qquad (2)$$

where A is stand age and a and b are coefficients estimated from regression.

The value of the b coefficient is a function of the basal area index, Ig, at a given age after decline has set in and thus can be estimated:

$$b = 2.275 - 0.5008 \ln Ig_{50}; \qquad (3)$$

$$(r^2 = 0.88)$$

where Ig_{50} is the basal area index at age 50 (rotation age). The coefficient b becomes 0 when Ig is 95.

Applying equation (1) to the phosphate trials produced, on the average, a yield class of the order YC 16 to YC 19 depending on the height index (Ih) associated with the type of site (fig. 1). That is to say, most stands growing at a level of productivity equivalent to YC 16-19 on particular sites are likely to be able to maintain sufficient P in their system to continue that level of productivity without amendment. The effect of applying OSP to stands in decline is illustrated in figures 2 and 3 and of applying mixed mineral fertilizer (containing phosphate) in figure 4. Various modes have been used ranging from single doses, both small and large, to frequently repeated small and moderate doses. A comprehensive review of phosphate fertilizing was made by Boardman (1974), and later developments in this subject have been discussed in Ruiter (1980).

Supply of phosphate as a primary nutrient factor influences growth rate above the minimum sustainable YC 16-19 level up to about YC 24, as figures 2 and 3 show. A response surface derived from data from a recent trial, which shows this primary dependency on sites with lateritic podzolic soils, is shown in figure 5. In this case N and P were varied, but were accompanied by sufficiency in all other nutrients as well as the site having complete weed control.

DECLINE IN PRODUCTIVITY IN SECOND ROTATIONS

In the late 1950s and early 1960s great concern was expressed at a decline in productivity in second rotation stands relative to productivity at the same age in the first rotation (Keeves 1966). There was direct evidence from measure-

1/ The mean height of the tallest 70 trees per hectare.

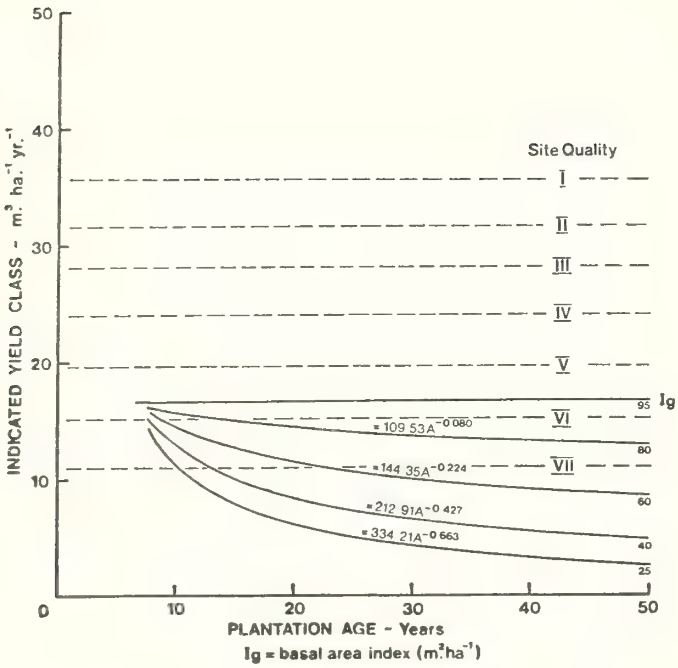

Figure 1.--Decline in "indicated yield class" with phosphate deficiency in unthinned stands.

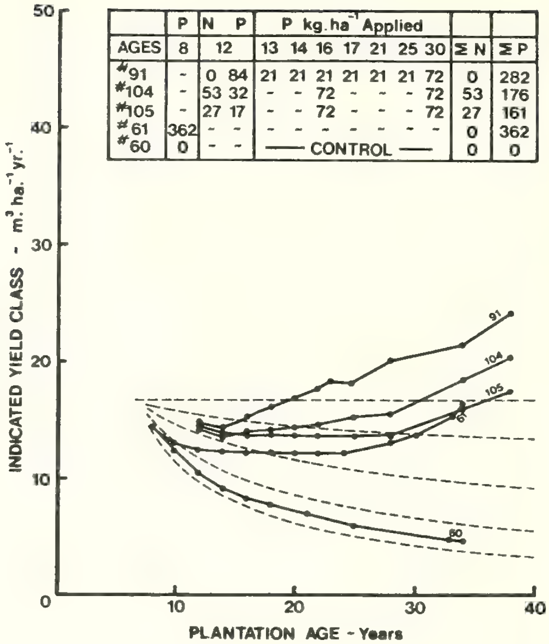

Figure 2.--Response to phosphate applications on lateritic podzolic soils illustrating rate x frequency effects.

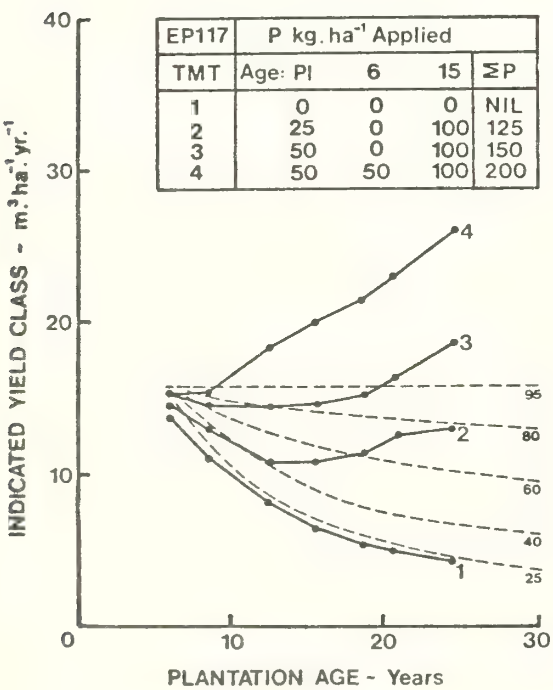

Figure 3.--Response to phosphate applications on groundwater podzols (spodosols) on aeolian sands illustrating rate x frequency effects.

ments made in many plots relocated in the same place as mensuration plots established in the first crop. This was supported on a broad scale by comparisons facilitated by the area survey method of site quality class assessment used as the basis of forest management (Lewis et al 1976). Decline was about 25 percent in volume over 85 percent of the plantations, which were then 10 years old in second rotation.

A considerable amount of research has been undertaken to reveal the factors affecting productivity in the long term and the ameliorating or detrimental effect if certain of the site factors are manipulated. This has served both to alleviate the problem and to shed light on the interdependence of ecological factors that sustain productivity (Theodorou and Bowen 1981).

A number of factors capable of silvicultural manipulation have been investigated, including combinations of factors in attempts to find the upper limits of Pinus radiata wood production in the southeast region (within the limitations of climatic factors). The general response achievable by the provision of significant ameliorating factors (most of which act additively) has been illustrated by Boardman and Simpson (1981) for radiata pine in South Australia and for southern pines growing in Queensland.

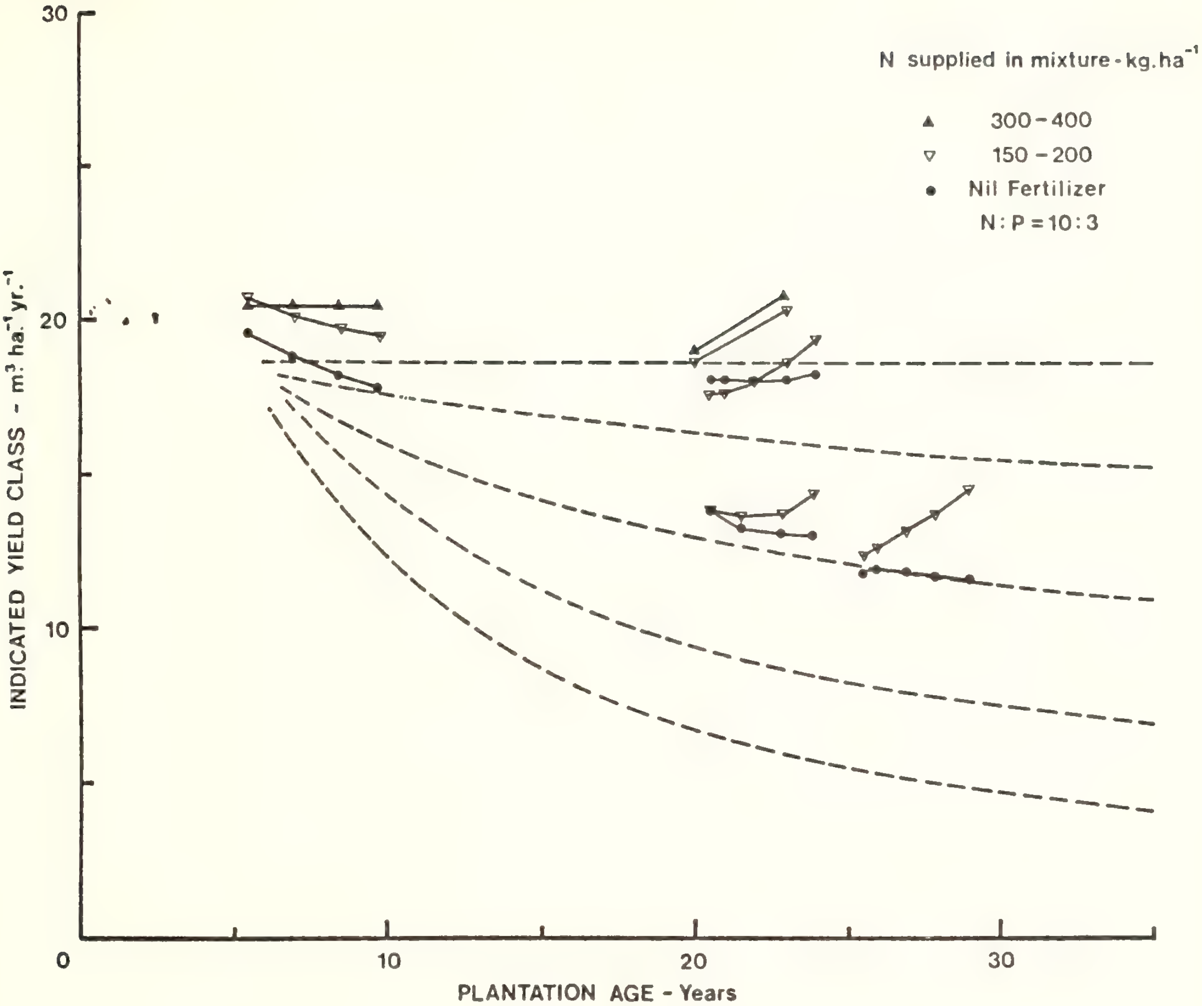

Figure 4.--Change in indicated yield class on podzolized aeolian sands in response to balanced mixed fertilizer after canopy closure.

Strong retardation of early stand development occurred in the second rotation under plantation establishment regimes used in the 1950s. This was particularly evident at ages between 4 and 6 years, even on non-marginal sites. It tended to coincide with maximum basal area per hectare increments. This period was before any significant external recycling of nutrients through litterfall was possible and pointed to nutrition as a significant factor. It was also clear, however, that it was more a matter of how nutrient supplies were transmitted to the trees, and this needed to be considered over the whole range of sites for this age group (Boardman 1978).

Two approaches were made:

(1) Investigate the effect of sustained competition control on growth (Boardman et al. 1979); and

(2) To present the young stands with a combination of nutrients in different amounts.

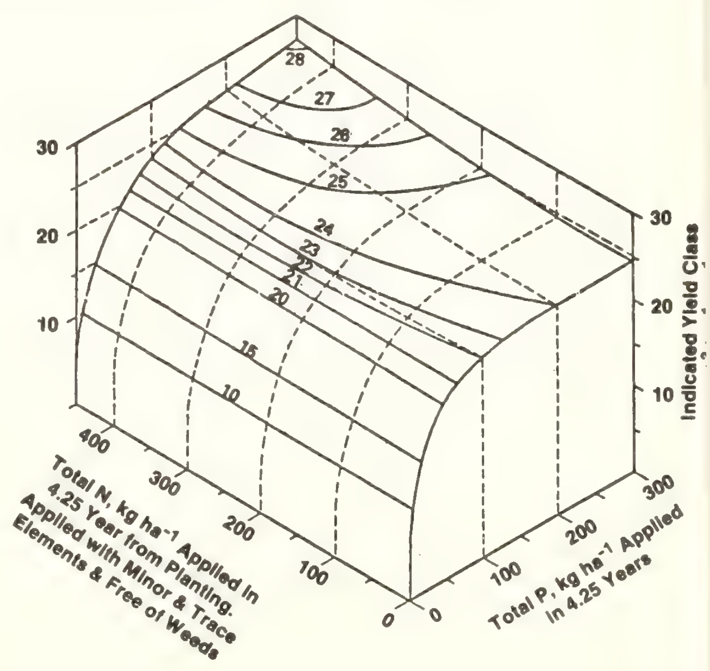

Figure 5.--Fertilizer (N x P) response surface for lateritic podzolic gr. sandy loams (Kuitpo series) in central region of South Australia.

Table 1--Indicated yield class resulting from early silviculture of *Pinus radiata* in the southeast region of South Australia on yellow podzolized aeolian sands

Trial	Plot	Years fert'd	Cult'n	Weed control	Fertilizer N	Fertilizer P	PLANTATION AGE 3	4	5	6	7	8
					- (kg ha^{-1}) -							
LT 73	5	P-4	Pl x 4	Good, 2y	360	58	30.6	31.2	32.2	32.2	33.4	33.6
RT 8	1	"	Pl x 2	"	375	60	-	30.6	30.8	30.1	29.2	27.9
"	2	"	"	"	335	53	-	30.0	29.7	27.9	28.5	27.4
"	3	"	"	"	325	52	-	33.9	29.9	27.2	27.5	25.6
"	10	"	Scalped	"	300	48	28.6	29.3	30.1	31.9	31.7	
"	11	"	"	"	300	48	33.9	32.5	32.8	34.1	32.9	
"	12	"	"	"	310	51	32.4	32.0	30.3	31.0	29.7	
"	13	"	"	"	300	48	30.5	32.7	32.7	33.7	36.4	34.9
"	14	"	"	"	300	48	36.5	37.2	37.6	38.2	38.6	38.4
"	15	"	"	"	300	48	34.0	33.6	33.6	34.8	34.1	34.2
"	16	"	Pl x 2	"	295	48	30.9	30.7	32.3	32.4	31.2	
"	17	"	"	"	295	48	33.2	33.6	32.7	32.9	31.7	31.8
"	20	"	"	"	300	50	37.8	36.7	36.3	35.3	34.4	
"	21	"	"	"	300	50	38.9	36.3	35.9	35.4	34.0	
"	32	"	"	"	300	50		32.0	30.7	29.5		
"	33	"	"	"	300	50		36.2	33.6	31.3		
"	34	"	"	"	300	50		37.0	35.0	33.0		
"	35	"	"	"	300	50		36.0	33.6	32.1		
PFR	Lands	"	Scalped	"	300	50	39.0		35.1			
MBFR	1	"	Pl x 1	"	300	50	35.1	35.1	35.0			
					Averages:		33.9	33.6	32.9	32.4	32.4	

Ingestad (1981) has reviewed the nutritional effect on trees and shrubs that normally grow on acid soils of controlled supplies of complete, balanced, liquid nutrient solutions. The importance of the balance between the nutrient components on optimal and suboptimal growth rates given adequate water and aeration has been stressed. By analogy, complete mineral mixtures balanced in similar proportions, relative to the pattern of uptake by radiata pine trees, were formulated in South Australia and modified only relative to expected differential release of elements from the mineral sources. They were based on whole-tree analysis of young trees in the southeast region (Project EM 72) augmented by data from Forrest (1969) and Will (1964). These have been applied in graduated doses relative to an expected rate of uptake associated with a given production trend (Woods 1976, 1977) and in major experiments with opportunity to vary both N and P (Boardman et al. 1979).

Competition from weeds has drastic effects on early growth rate (Cellier and Stephens 1980; Nambiar and Zed 1980). In all current field experiments deliberate control of competing vegetation is rigorously carried out in order to remove this major source of uncontrolled variation. Table 1 shows temporal trends in indicated yield class for a number of trials. Figure 6 shows the consolidated response surface of yield class development with time for given levels of balanced, mixed-fertilizer input. This figure relates to the yellow-colored podzolized aeolian sands in the southeast which form about three-quarters of all the soils afforested with pines. Rate of the balanced, complete fertilizer is referred to by its N content. For example, at the level shown as 100 kg N ha^{-1}, the mixture also supplies 30 kg P, 68 kg K, 173 kg Ca, 2 kg Mg, 180 kg S, 20 kg Fe, 3 kg Cu, 3.5 kg Zn, 0.5 kg Mn, 0.02 kg B, 0.01 kg Mo, and 0.002 kg Co. Although this fertilizer mixture was devised as a research product, it does appear to offer the root system a balanced set of nutrients to draw upon and it has been used in general practice. The mixture is wholly granulated to maintain distribution of components, reduce dust hazards, and ease bulk handling. Two other granulated fertilizer mixtures have been prepared. One is this basic mixture supplemented by superphosphate. The other is a seven-element mixture containing a higher component of nitrogen per tonne.

Methods are available to effectively control all common weed species except bracken fern (Boardman

and Boomsma 1980). This latter species occurs commonly on many of the yellow podzolized sands, particularly on the deeper soil phases as well as upon their more heavily leached "white" counterparts. Figure 7 is a response surface sketch for stands that are infested with bracken fern (derived from limited data, correlated with fig. 6). It attempts to show the impact of bracken fern on the early development of yield class. The overall difference at ages over 5 years from planting from the equivalent sites free of weeds is of the order of 7 yield class units ($m^3.ha^{-1}.yr^{-1}$). The application of the mixed mineral fertilizer certainly increases growth rate, crown density and it reduces time to canopy closure. Indications are, however, that there is little likelihood of ever gaining the yield class potential on sites where competition can be effectively achieved.

Young plantations that are too old to have received the balanced mixed set of treatments (Woods 1977) show similar but more aggravated reaction to bracken fern competition. These stands are generally of YC 15-22 and are spindly in form. They were either fertilized only with zinc or superphosphate in the early years or not fertilized at all. Recently, the mixed, balanced fertilizers have been applied in conjunction with the first thinning operation. Some remarkable increases in indicated yield class have occurred after such applications, and improvements have been sustained for several years in most cases. Figure 4 illustrates some of these responses against the background of the phosphate deficiency trends shown in fig. 1. The age at which the stands are treated appears to be important in relation to the dose that is applied to sustain a growth rate above YC 19-20.

These results suggest strongly that bracken fern-infested sites that have been treated with the stepped mixed fertilizer sequence initially could be given further impetus from a second fertilizer input delayed until the stands have an initial thinning which is scheduled when the predominant height is about 20 m. The latest results suggest that fertilization may be best if delayed for a season after thinning. In this way, abrupt changes in ring width and basic wood density can be reduced. In any event, it seems the most likely way to bring stands into the latter half of the rotation at yield classes comparable with those from sites free of bracken fern. At first there is competition from bracken; this is followed by the intense intraspecific competition of the so-called thicket stage during which stemwood volume current annual increment (c.a.i.) culminates. Only after this is there an opportunity to influence the form of the c.a.i. trends. Our trials provide a practical illustration on ways the current increment trends may be managed during the rotation to best meet the aims of management. The influence of fertilizer on the form of c.a.i. trends has been cogently argued by Miller (1981) and Attiwill (1982) (for phosphate).

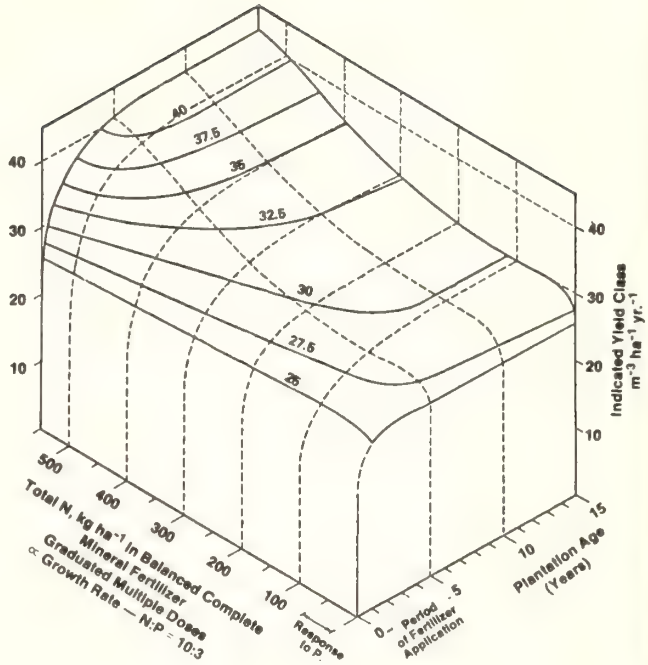

Figure 6.--Response surface of yield class development with time for given fertilizer inputs on yellow podzolized aeolian sands (Mt. Burr sand) in southeast of South Australia.

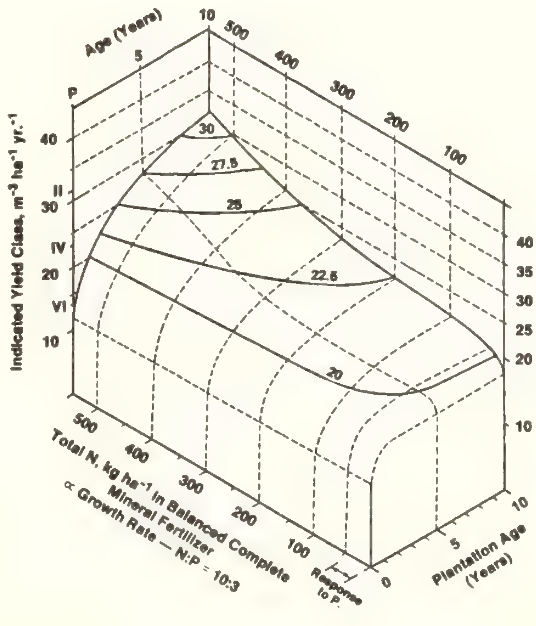

Figure 7.--Response surface of yield class development with time for given fertilizer inputs on bracken fern-infested yellow podzolized aeolian sands (Mt. Burr sand) in southeast of South Australia.

CURRENT INTERESTS

Two features of the pine plantation ecosystem are of vital interest at the present time. The first feature is the organic matter status. In the sandy soils, organic matter is the principal (often the only) source of base exchange. Its depletion is therefore to be avoided (Flinn et al. 1980). At present, there are indications that excessive amounts accumulate on the surface in many stands in South Australia (Florence and Lamb 1973) in contrast to other stands, including Pinus radiata in South Africa (Versfeld 1981). Ameliorative treatments that accelerate breakdown and release rates for C, as well as nutrient elements, have been found experimentally, but none represent a basic solution to the problem. The second feature, soil compaction, is related to the first. Sands et al (1979) have described subsurface compaction in these soils after nearly a rotation of pines. The compaction is correlated with depletion of organic matter within the solum. Increase in soil compaction in the rooting zone is sufficient to be regarded as potentially growth inhibiting (Greacen and Sands 1980).

Increases in the amount of litterfall, earlier development of a pine forest floor, improved nutrient content of litter, and improved rate of nutrient cycling have resulted from comprehensive balanced fertilizing. Fertilizing has produced significant gains in productivity as well as showing that sustained continuity in growth rate is possible even at enhanced rates which have not been previously achieved. The mode of fertilizer application in graduated or stepped, balanced doses, proportional to growth rate targets, appears to be an efficient way of fertilizing both young and mid-rotation stands. This mode of fertilizer application is particularly suited to a range of sites that are naturally only able to produce sustained growth from YC 16 to YC 26, or are subject to a decline in growth rate caused by phosphate stress.

The fertilizer response pattern is strongly suggestive of intrinsic feedback factors that affect the rate of metabolism and, consequently, the sustained rate of growth. This is reminiscent of the findings of Ingestad and Lund (1979) for stable, nonoptimum levels of nitrogen. The exponential method of dosing used in our field studies is meant to reduce the discrepancy between a constant rate of nutrient supply and the increasing size of the crop biomass. The results indicate that both phosphate and nitrogen applied in this manner may create stable nutrient levels in the plants and serve to maintain given growth rates. It is interesting that Ingestad and Lund (1979) consider that the decisive factor for stable suboptimal nitrogen status is not primarily the concentration in the nutrient solution, but the amount added per unit time in relation to net uptake rate at the given level. This feature may help to explain the effectiveness of the granulated, balanced, mixed fertilizer, an analogue of the balanced mixed nutrient solutions used by Ingestad and Lund (1979). These aspects are worth further investigation.

The method of "stepped-ramp" fertilizing also appears well suited to trees with the magnolioid root system--the thick-root strategy of the pines. Pines with magnolioid root systems are likely to respond to fertilizers over a much wider range of soils in South Australia, and possibly elsewhere, by simulating a nutritional supply situation that is richer and more episodic than in the native Australian forests.

DISCUSSION OF IMPLICATIONS FOR CONTINUING PRODUCTIVITY

Marked progress has been made to overcome the decline in productivity in second rotations. There are a number of silvicultural practices that, in combination, alleviate growth-limiting stresses on young trees in plantation.(Fig. 8)

Considerable progress has been made in producing sustainable growth rates on first and second rotations by use of balanced mixed fertilizers over a wide range of acceptable yields. Nutrient inputs have been raised to levels sufficient for sustained levels of metabolism. In this respect, control of competing vegetation is important because its withdrawal of soil moisture effectively deprives young trees of nutrients and also effectively shortens the growing season.

Studies have also indicated that an alternative method of nitrogen enrichment through use of legumes late in the rotation or interrotation may enhance organic matter status. This is under active investigation. It is desirable for this alternative to provide something other than direct nutritional benefits, as a recent economic evaluation showed no difference in the cost: benefit ratio at current prices.

It now appears possible to manipulate growth rates above a given desirable minimum to meet both quantity and quality objectives on a proportion of sites. Of these sites the most readily manipulable ones are those below about YC 25, the marginal forest sites. It is on these sites that chronic effects of nutrient shortfalls may occur in the growing season. Even in stands where productivity has been raised to as high as YC 35, it has been apparent that chronic and even acute effects can be induced in the short term. The use of balanced, complete types of mineral mixtures is, at least, likely to mitigate against prolonged chronic shortages of growth-limiting nutrients. Balanced fertilizer mixtures can be even more effective if other site factors are ameliorated to an extent which permits their potential to be revealed. Most interesting of all, however, is the possibility that such mixtures will allow control of growth rate through control of chronic nutritional problems, especially phosphate, and at higher yield potentials of nitrogen, to meet quality and quantity criteria.

Fertilizing and competition control, together with improvements arising from tree breeding, are bringing closer the time when silviculturists can modify sites to produce and sustain acceptable growth rates in the broadest sense of that term.

Our choice of crop species has much influence on the scope forest managers may have to manipulate growth rates. The species largely define the biochemical and chemical conditions that permit sustainable growth to be attained.

Forest managers need to think of the plantation as an ecosystem in its own right and have an understanding of the processes that influence productivity as stands increase in age. Only then will there be an opportunity to influence those processes that dominate the growth rate, both to meet management objectives and to optimize the efficiency of site use by the selected crop trees. This will allow the manager to conserve resources that contribute to acceptable levels of sustained productivity.

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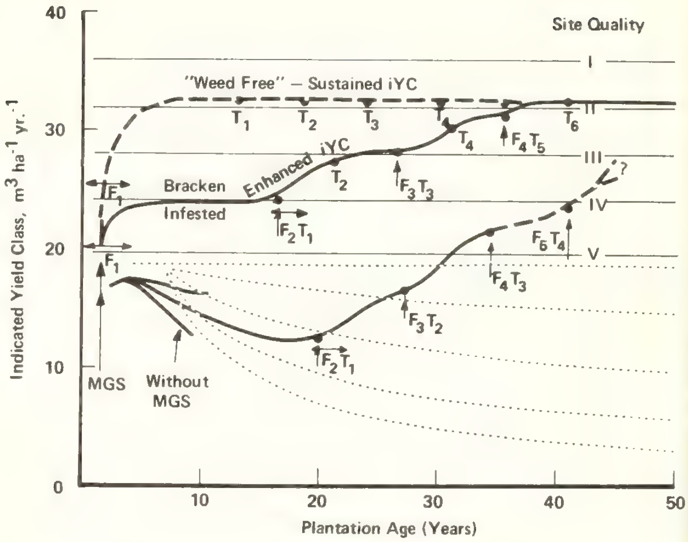

F_n = Fertilizer Application, n^{th}, in Sequence

T_n = Thinning Operation, n^{th}, in Sequence

Figure 8.--Prospective gains in indicated yield class from deficiencies induced by site factors.

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FOREST FERTILIZATION IN SWEDEN

Göran Möller

ABSTRACT: Forest fertilization in Sweden is based on applied research work since the end of 1950´s. Prediction functions for growth response in cubic meters per hectare are developed from 933 fertilized plots in 234 different locations. The functions have shown that 6 different stand and site factors significantly influence the growth response as well as the dose and course of nitrogen. Operational fertilization covers today about 150 000 hectares per year and has increased the yearly growth by 2.5 million cubic meters.

Applied research on forest fertilization started in Sweden in the last years of 1950´s and the beginning of the 1960´s. Before that, some basic research (Tamm 1956) had shown that nutrient supply to a forest stand on a poor site could give a positive growth response. But in the late 1950´s several Swedish forestry companies and some interested individual foresters at the Swedish State Forest Service established some fertilization trials on their own. The first results were very encouraging but also showed some unexpected effects, and there were too many problems for each company to solve alone. As a result the fertilization section of the Institute for Forest Improvement was established in 1967 to coordinate and direct the further applied research in forest fertilization. All the forest companies as well as the Private Forest Owners Association contributed to this institute, as did the government.

All fertilization trials established were registered and analyzed in a uniform way, quite independent of ownership. The first results were published in 1971 (Möller 1971), and the first preliminary forecast were released in 1973 (Möller 1973). In the meantime a great number of complementary trials had been established by the institute to cover the whole country and broaden the soil and stand conditions for the different trials. The new trials were gradually analyzed; and in 1979 all the available data (a total of 234 trials with 933 plots treated in different ways) were combined to create a more reliable prediction function by using regression analysis (Rosvall 1979) (fig. 1). This work gave a better understanding of how different stands of pine (Pinus sylvestris L.) and spruce (Picea abies (L.) Karst.) will respond to nitrogen supply and is the basis for the forest fertilization program in Sweden today.

Even before nitrogen had been found to be the only nutrient that gave a significant positive response during the first 5 years after application. Now Rosvall found that no fewer than 8 other independent variables (Table 1) influence the response in different ways. The most important are the dose of nitrogen, the source of nitrogen, and the current growth of the stand. Site quality, latitude, altitude, stand age, and tree species significantly influence the growth response also.

By holding some variables at constant values we can study how different factors influence the results. The influence of an increased nitrogen dose from different sources is shown in figure 2. The site quality is expressed as height in meters at age 100 and is allowed to vary, but all other variables are held constant. We can see how the growth increase in cubic meters per hectare during

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the first 5 year period is much higher for the same nitrogen dose when given as ammonium nitrate compared with urea. We can also see how the growth response increases almost as a straight line when the nitrogen dose is increased on a poor site (site index 16 m), but starts to bend at about 125 kg when applied on a good site (site index 30 and 32 m).

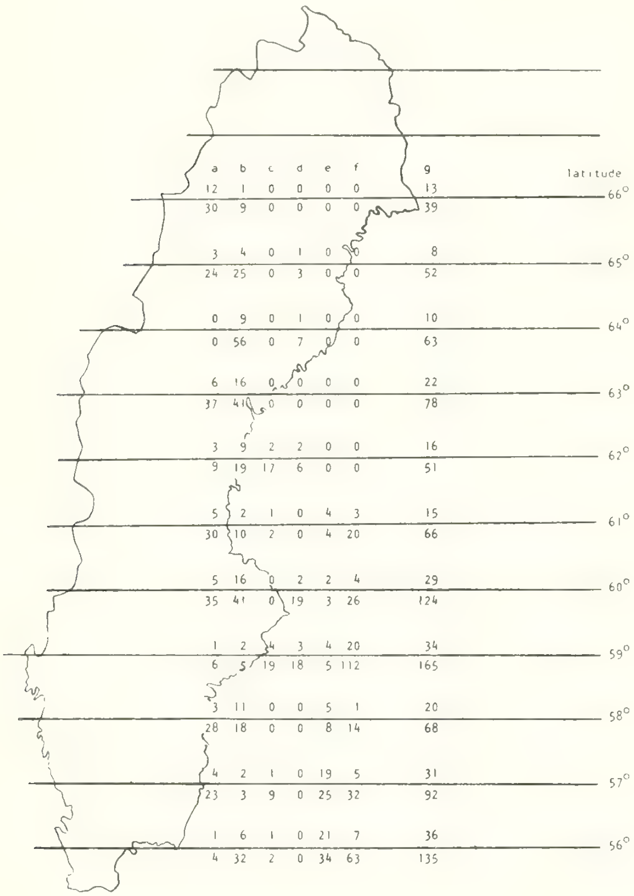

Figure 1.--Trials behind the prediction functions of 1979.

Table 1.--Independent variables influencing the growth response.

DOSE OF NITROGEN
SOURCE OF NITROGEN
CURRENT GROWTH OF THE STAND
SITE QUALITY
LATITUDE
ALTITUDE
STAND AGE
TREE SPECIES

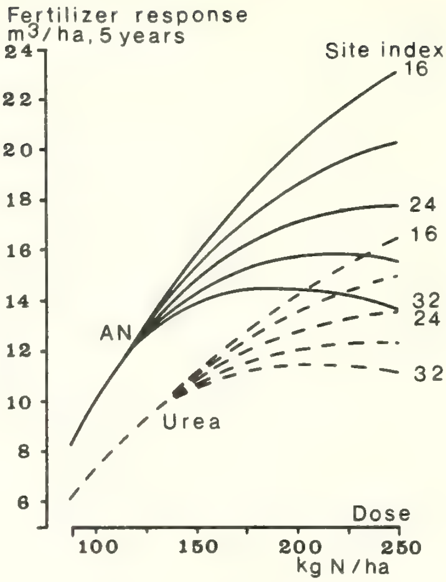

Figure 2.--Correlation between growth response and nitrogen dose, source of nitrogen, and site quality.

The influence of latitude (fig. 3) is rather important south of 60° N., but insignificant north of that latitude. Elevation (fig. 4) provides for an optimum response 200-300 m above sea level. A very strong variable is the current growth of the stand when all the other factors are held constant (fig. 5). The better the current growth is before fertilization, the better growth response in cubic meters per hectare will be obtained. A middle-age stand (fig. 6) will respond better than a young or old one with the same current growth. This indicates differences in stocking density between stands (all other factors held constant). The influence of different tree species (fig. 7) is rather small and will be evened out over a long period as response time is longer for spruce than for pine.

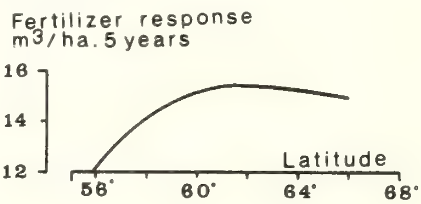

Figure 3 .--Influence of latitude on the growth response.

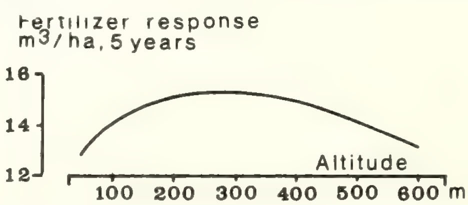

Figure 4.--Influence of elevation on the growth response.

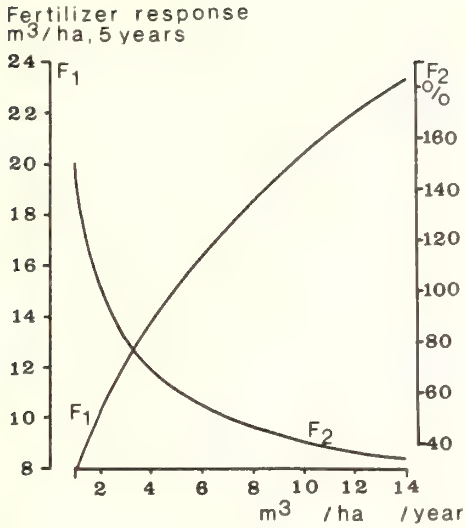

Figure 5.--Influence of current increment on the growth response.

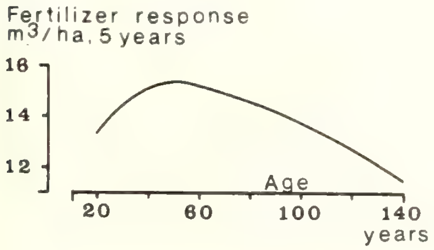

Figure 6.--Influence of stand age on the growth response.

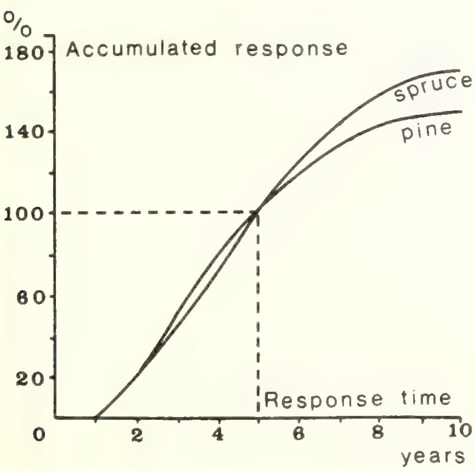

Figure 7.--Influence of tree species on the response.

The prediction function, which is complicated to use without a computer, has been translated to a set of response curves for different site qualities (fig. 8). By selecting appropriate curves for the site quality in question you can easily read the expected growth increase in cubic meters per hectare during a 5-year period for a 65-year-old pine stand at latitude 60° N. and 200 m above sea level when the current increment of the actual stand is known. There are special tables of correction factors for other source of nitrogen, different latitude, elevation, tree species, age, and period length.

The area of forest yearly fertilized in Sweden is continually influenced by the knowledge of biological effects, by predictions of future demand for wood, and by the different forest owners´ available money in relation to nitrogen fertilizer costs. From 1962 to 1964 the forest fertilization on mineral soil (Table 2) increased from only a few thousand to more than 100 000 hectares (Holmen 1973). Then, during the last years of the 1960´s, there was a decrease in fertilized area, mainly as a result of some years with rather bad economic results for the forest companies. In the 1970´s, the fertilized area increased again almost up to 200 000 hectares, when the economy was hit by the oil crisis and rapidly increasing fertilizer costs. The area dropped to 132 000 hectares in 1979 but is now increasing again as the forest companies are recovering from the oil crisis. Although there are no reliable figures available for 1981, the area is expected to be between 150 000 and 175 000 hectares.

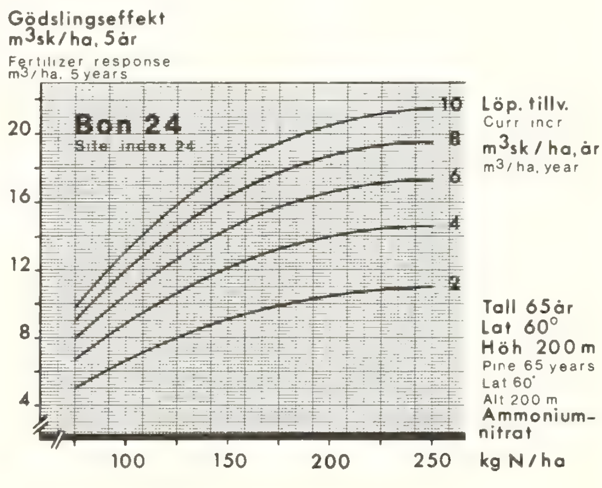

Figure 8.--Example of a set of response curves valid for site quality H_{100} = 24 m.

Table 2.--Fertilized area in Sweden 1962-1980, mineral soil.

Year	Mineral Soil Fertilized (ha)
1962	4 017
1963	5 996
1964	11 500
1965	40 208
1966	106 131
1967	100 285
1968	81 026
1969	77 710
1970	84 187
1971	119 775
1972	114 597
1973	121 091
1974	167 369
1975	157 379
1976	188 750
1977	186 114
1978	133 298
1979	131 676
1980	160 094

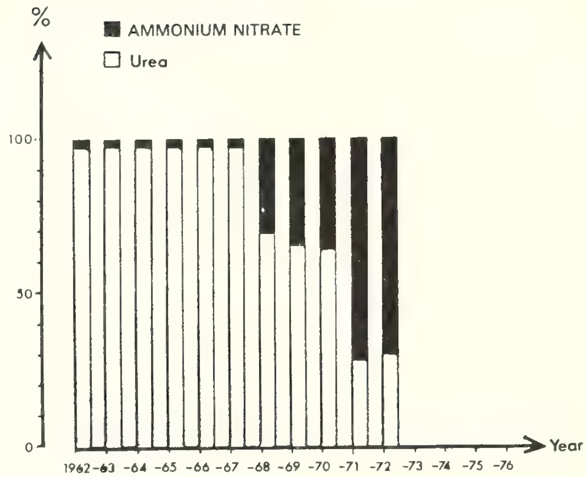

Figure 9 .--Percent nitrogen applied as urea and ammonium nitrate.

From the beginning of operational forest fertilization, the source of nitrogen was almost solely urea (fig. 9) until the first, more reliable results were obtained showing the superiority of ammonium nitrate in 1968. After that, the proportion of ammonium nitrate used as a nitrogen fertilizer gradually increased as more and more trial results showed the big advantage for that source of nitrogen. From 1979 on, practically all fertilization has been performed with ammonium nitrate.

The dose of nitrogen (fig. 10) was initially 60 kg ha^{-1} but increased in time with research findings. Since 1971, dosage has ranged from 145 to 150 kg ha^{-1}, which is the average dose recommended today.

The application (Table 3) has mainly been done by aerial methods. From the beginning, only fixed-wing aircraft were used in operational scale but since the middle 1970's the use of helicopters has rapidly increased and there are some indications that tractors will be commonly used in the future. Only a small part of the fertilizer is spread by hand.

Forest fertilization on peat soils (Table 4) is still done on a very small scale in Sweden. The area has varied between approximately 500 and 3 000 ha yr^{-1}. The reason for that may be because of the uncertainty of growth response and duration on different peat soil types and for different amounts of various macronutrients and micronutrients. Another consideration is the much higher costs per hectare that are associated with drainage and fertilization on peat soils compared with only fertilization on mineral soils.

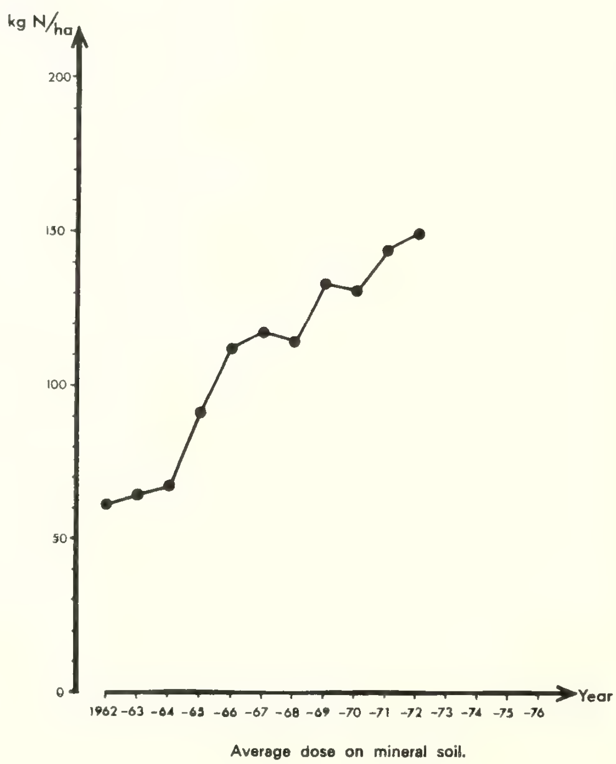

Figure 10.--Dose of nitrogen used in practical forest fertilization in Sweden.

Table 3.--Development of application methods in applied fertilizer amounts on mineral soils.

Application Method	Year	Area of Mineral Soil Fertilized	
		(ha)	(%)
Fixed-wing aircraft	1976	123 755	66
	1977	104 084	56
	1978	70 208	53
	1979	78 285	59
	1980	85 832	53
Helicopter	1976	61 991	33
	1977	74 605	40
	1978	54 612	41
	1979	47 217	36
	1980	66 597	42
Tractor	1976	2 286	1
	1977	6 945	4
	1978	8 120	6
	1979	6 077	5
	1980	7 549	5
Broadcast	1976	718	-
	1977	480	-
	1978	358	-
	1979	97	-
	1980	116	-

Table 4.--Area of peat soil fertilized in Sweden 1962-1980.

Year	Peatland Fertilized
	(ha)
1962	749
1963	1 102
1964	1 021
1965	765
1966	906
1967	665
1968	978
1969	2 049
1970	372
1971	1 006
1972	295
1973	1 783
1974	838
1975	1 489
1976	377
1977	1 646
1978	2 363
1979	1 447
1980	2 778

Fertilization in operational scale is almost exclusively performed by the State Forest Service and a rather small number of big forest companies. In 1980 81 percent of the total fertilization was done by the four biggest companies and the State Forest Service. The 15 biggest companies including the State Forest Service account for 95 percent of the fertilized area in 1980. There is a small tendency toward increasing fertilization within the small- and average-sized forest companies. Very little fertilization is done by the private forest owners who account for about 50 percent of the total forest land in the country.

In total, more than 1,7 million hectares have been fertilized since 1962 and about 180 000 hectares have been fertilized two or three times (Holmen 1982). It has been calculated that the wood production in the country is increased by approximately 2.5 million m^3 yr^{-1} because of forest fertilization, which corresponds to the yearly wood consumption in one of the biggest pulp mills in Sweden. During the years 1976-80, the share of nitrogen fertilizer used in forestry has varied between 7.5 to 10.5 percent of the total consumption in the country.

Two of the most important research objectives are to determine on which sites micronutrient deficiencies can occur and how the increasing nitrogen supply from air pollution --together with the sulphur dioxide--, may influence the fertilizer response in different areas. Growth disturbances from boron deficiency on mineral soil in the northern part of Sweden was determined in the late 1970's. The boron concentration in pine needles seems to be very low in the far north area of Sweden but seems to increase toward the south in the same way as the boron concentration in stream and lake waters increases from north to south (Ahl & Jönsson 1972). An application of 150 kg N ha^{-1} has been shown to decrease the boron concentration in the needles by 4-5 ppm on the average, which means that growth distrubances in the needle biomass are very likely to occur in the northern region. Even though growth reduction or decreased nitrogen growth response has not yet been statistically proven, the Institutet for Forest Improvement recommends that companies use a boron-nitrogen fertilizer with 0.2 persent boron when fertilizing in region 1 where the boron concentration in the water lies between 0-4 $\mu g\ l^{-1}$. In region 2, where the boron concentration lies between 4-8 $\mu g\ l^{-1}$, it is recommended to use the same boron-nitrogen fertilizer when refertilizing the stands. We hope that further research will provide more detailed recommendations in the future.

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FOREST FERTILIZATION RESEARCH IN DENMARK: RESULTS AND PERSPECTIVES

H. Holstener-Jørgensen

ABSTRACT: The paper contains a brief geological-pedological and historical account as a background for the research in fertilization of forests and plantations in Denmark. This research has shown that stands on former heather-clad sandy areas in Jutland may advantageously be fertilized with NPK-fertilizer (125 kg N per hectare and 5 years) 10-20 years before rotation.

On old forest soils (the islands and East Jutland) there is generally no effect of fertilization except as far as the growing of decoration greenery and Christmas trees is concerned, for which the removed nutrients must be substituted by fertilization.

In 1980, about 8.700 hectares were fertilized in Denmark, and about 713 tons of N were applied, mainly as NPK-fertilizer.

In the near future research will concentrate on further investigations into the interactions between fertilization and irrigation.

NATURAL CONDITIONS

Danish forests and plantations grow mainly on moraine deposits from the last glacial age (the old woodlands), outwash plains from the melting of the ice, and the hill islands in the west, which are deposits from an earlier glacial age.

Under the Forest Act of 1805 the forests in the old woodlands were subjected to preservation regulations, and grazing was prohibited. This means that these forests, however mistreated they might have been at the time of preservation, have had 175 years to become restored to their original soil condition. Weathering of a relatively fertile morainic material and an input of nitrogen and other plant nutrients through precipitation and dust have contributed to the process, and there is little reason to expect that nutrient shortage should be growth-inhibiting in these localities.

Exceptions are areas used for production of Christmas trees and decoration greenery. The removal of these products breaks the recirculation of plant nutrients by way of the litterfall, and the soil may eventually be exhausted if the removed plant nutrients are not restored.

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It is a different matter on the outwash plains, the hill islands, and the areas of diluvial sand where farming has exhausted the soil of plant nutrients, and large areas have become overgrown with heather. These heathlands have been the object of afforestation that since 1805 has contributed to increasing the percentage of forest in this country from just under 4 percent to 11.6 percent. In these poor soils the restoration is slow, and 100 years of experimental work has shown that the nutrient level is too low to secure optimum growth under the given climatic conditions.

EXPERIMENTAL EVIDENCE

Norway Spruce

Since the last quarter of the 19th century experiments have been directed toward soil improvement and fertilization in plantation areas and old woodlands. Names like P. E. Muller (1840-1926, soil investigator of world renown), J. Helms (1865-1934, state forest supervisor and afterwards professor of forestry), L. Smith (1868-1931, forest supervisor under The Danish Heath Society), Fr. Weis (1871-1933, professor of plant physiology), E. Oksbjerg, and C. Mar:Møller (1891-1978, professor of forestry) mark this experimental work.

It is characteristic that by far the greater part of the experiments were carried out in plantations. They have shown that, while fertilization has only rarely had any effect on the better moraine soils, there is almost certainly an effect on afforested heathland. Up to about 1960, the experiments were interpreted as follows:

Responses were normally obtained from application of nitrogenous fertilizer to conifer plantations on former heath. But though the effect was great in relative measures--frequently 25 percent or more on top-shoot lengths--fertilization was not considered economically feasible. The long rotation period on the heathlands means a long period during which interest is to be paid on the investment made at the time of planting.

In addition, some experiments showed that if legumes are to be established in the plantations, potassium and phosphatic fertilizers must be supplied.

Later experiments in localities on sandy soil showed that the matter is probably more complicated than that. Fertilization with only a single plant nutrient will often induce deficiency in one or more other plant nutrients (Holstener-Jørgensen 1964), and in many experiments the greatest effects were obtained in NPK fertilized plots (e.g. Møller, Scharff, and Dragsted 1969).

In the 1960's an experimental program was started in Norway spruce, which were fertilized about 10 years before the normal local rotation age. The experiments were carried out by The Danish Forest Experiment Station and The Danish Heath Society and were established all over the country. These experiments confirmed the knowledge obtained in the early experimental work.

Figure 1 shows the relationship between excess increment and current increment of basal area in the control plots after nitrogen fertilization in four localities on sandy soil in Jutland (Holstener-Jørgensen and Bryndum 1973). The

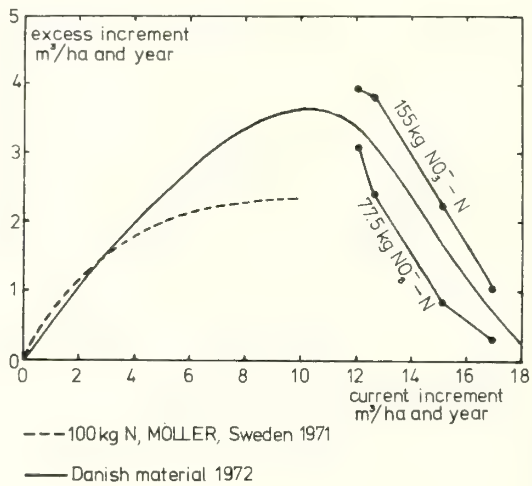

Figure 1.--The relationship between the excess increment after nitrogen-fertilization and the increment in the control plots in four localities on sandy soil in Jutland.

stand ages were from 70 to 80 years, and the precipitation during the 5-year experimental period was relatively favorable. The dots, which are mean values for three replications in each experimental area, are connected with lines. The dashed curve is an adjustment curve for application of 100 kg urea-N to Norway spruce in Sweden (Moller 1971), and the solid curve is an adjustment curve combining the two sets of observations. It appears that the excess yields are falling with rising increment level in the Danish material, and it is indicated by incorporation of the Swedish investigations that the excess yield from the poorest site class is approximately the maximum excess yield that may be expected. The drop to close to zero in figure 1 is in keeping with the fact that it has been impossible to demonstrate any certain effects of fertilization of Norway spruce in localities better than these sandy soils in Jutland (Holstener-Jørgensen and Bryndum 1975).

The variations in precipitation during the growing season from one year to another have a great influence on the increment (Holmsgaard 1955).

There is a considerable positive interaction between water supply and supply of nutrients (Holstener-Jørgensen and Holmsgaard 1975).

Figure 2 shows lengths of top shoots during the first 3 years in a fertilization and irrigation experiment in young second-generation Norway spruce in Gludsted plantation, which was established on a former heather-clad heath plain. The lengths of top shoots are plotted against the heights to adjust for initial differences in growth in the area.

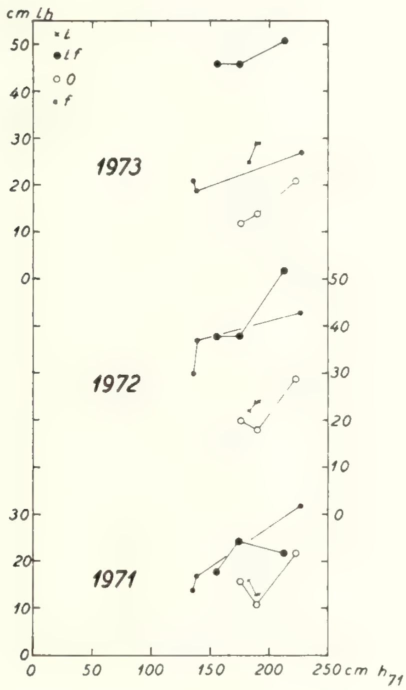

Figure 2.--Mean lengths of top shoots (cm i_h) plotted against initial heights (h_{71}) in each plot.

It appears that in 1971 there is a minor effect from fertilization, but none from irrigation. In 1972 the effect from fertilization is quite clear, but still there is no clear effect from irrigation. In 1973 the picture is a different one. The exclusively fertilized and the exclusively irrigated plots are on the same level, somewhat above that of the control plots. The plots both irrigated and fertilized are on a considerably higher level. There is a clear positive interaction between irrigation and fertilization.

Figure 3 shows the annual basal-area excess increments in 80-year-old Norway spruce in the Gludsted plantation (heath plain) after fertilization in the spring of 1965 with 500 kg (N_1) 1000 kg (N_2) calcium nitrate and 3000 kg superphosphate (P) per hectare, and repeated fertilization in the spring of 1970 with the mentioned quantities of N.

The figure shows that the effects of pure N fertilization are greatest in the first period when the precipitation was comparatively high.

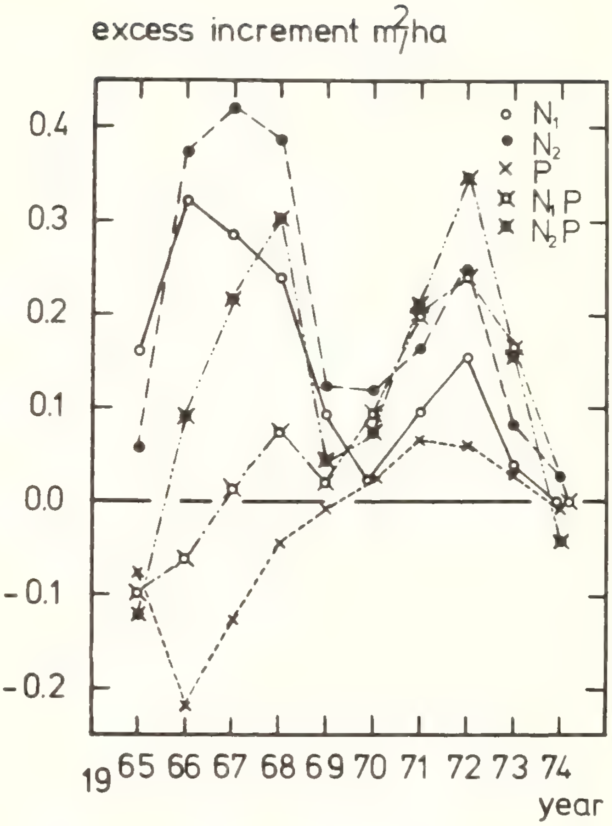

Figure 3.--Basal-area excess increments in 80-year-old Norway spruce after fertilization in 1965 and 1970 with 500-kg (N_1) and 1000-kg (N_2) calcium nitrate per hectare, and in 1965 with 3000-kg superphosphate (P) per hectare.

In the second period with lower precipitation the effects were almost halved (see table 1).

Table 1--The mean precipitation for selected periods and months at Karup, Denmark

	Mean precipitation		
	May	June	July
	- - - - - - -	(mm)	- - - - - - -
Mean 1965-69	61.2	60.2	64.0
Mean 1970-74	45.0	41.2	87.0

The figure also shows that P fertilization has had a negative effect in the first period. In the second period the effects of NP are greater than the pure N effects. The heavy dose of superphosphate completely scorched the floor vegetation of mosses, and presumably it also

damaged the uppermost root system of the spruce with a resultant decline in increment.

Finally, the figure shows that the effect of N fertilization subsides after a lapse of 5 years in Danish localities on sandy soil.

A working party under Skovstyrelsen (State Forest Service under the Danish Ministry of the Environment) has summarized the preliminary results of the fertilization experiments on sandy soil (Skovstyrelsen 1976). Figure 4 shows the main results of this work. The two lighter curves show high and low mean excess yields from the Experiment Station's experiments in their third to fifth year. High excess yields are obtained in years of high precipitation, low in years of low precipitation. The heavy curve is a mean estimate, and the point on this curve is the mean of 15 experiments established by the Heath Society. The set of curves form the basis of the fertilization in practice in the areas of sandy soil in Jutland, and financial calculations show that a reasonable return is obtainable on investments made 10 to 20 years before rotation age; 125 kg N per hectare is used at 5 yearly intervals. Considering the interactions found and the deficiencies induced, the application of a mixed fertilizer (23-3-7 with Mg and Cu) with the following nutrient content is recommended: 22.6 percent N, 2.9 percent P, 6.6 percent K, 1.6 percent Mg, 0.1 percent Cu, and 0.02 percent B. On hill-island localities in West Jutland where P deficiency has been generally ascertained, a mixed fertilizer with a somewhat higher relative P content is recommended.

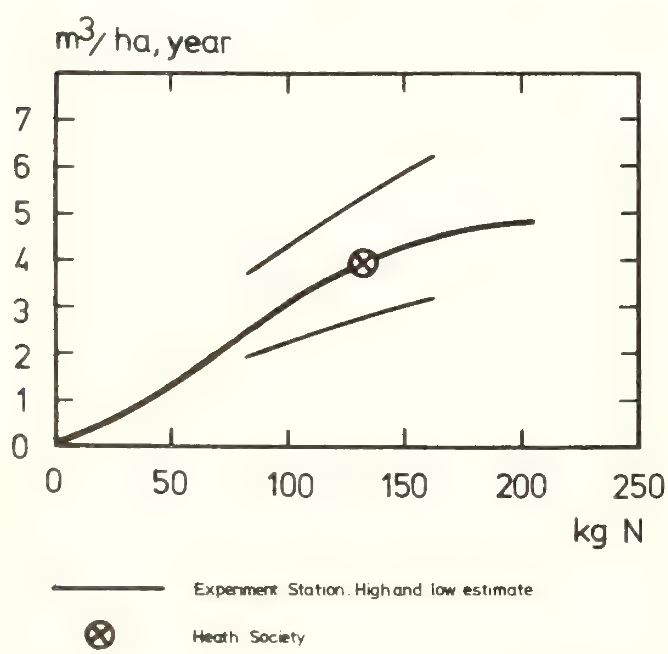

Figure 4.--Prognosis curves for fertilization of Norway spruce on sandy soil.

Decoration Greenery

Plant nutrients are carried away from sites where species are grown for decoration greenery and Christmas trees, and if the fertility of the soil and thereby its production capacity is to be maintained, the removed nutrients must be restored. An obvious basis for such a restorative fertilization is an examination of how much nutrients are removed per ton of marketable commodity.

An examination of four representative stands of noble fir (Abies nobilis) during 3 years shows that by cutting of the fourth, fifth, or sixth whorl from the tops of trees the quantities of nutrients per 1000 kg of marketable commodity shown in table 2 are removed (Holstener-Jørgensen 1971).

It appears that the closer to the top the tree is cut, the greater the amount of nutrients removed. In the cutting of younger branches the needles constitute a greater part of the product than in the cutting of older branches. The concentration of nutrients is higher in the needles than in the wood and bark of the branches.

These figures have been used to work out a formula for restorative fertilization and are shown in table 3 (Skovbrugstabeller 1979). The NPK fertilizer 23-3-7 with Mg and Cu has been mentioned earlier; however, it is comparatively new on the market, and may not always be obtainable, although it is marketed as an all-year garden fertilizer. The table therefore gives a formula for two other types of fertilizer, which have been on the market for many years: Nitrophoska (or Hoechsts) which contains 12.0 percent N, 5.2 percent P, 14.1 percent K, 1.2 percent Mg and 0.1 percent B, and $Ca(NO_3)_2$ which contains 15.5 percent N.

The doses in table 3 are greater than the mean values in table 2 because they have been adjusted to cover the greatest ascertained removals. This ensures that sufficient quantities of plant nutrients are supplied. The value of the product is great enough to justify an extra insurance premium.

Simultaneously with these investigations, a number of fertilization experiments have been made in noble fir stands. These experiments were established in previously unfertilized stands in which cutting had been done systematically for some years. Foresters are individualists. Some hold that stands of decoration greenery should be of a comparatively low stem number, so that all trees have maximum light. Many think that a greenery production may be obtained on water sprouts that are developed on the stems after cutting of the main branches. Others, perhaps more realistically, wish to preserve the greatest possible number of stems, realizing that the production primarily takes place on the regular whorls. A program involving the whole country

Table 2--Average nutrient concentrations (percentage or ppm in dry matter) in *Abies nobilis* at the cutting in various whorls, and amounts of nutrients (kg or g) per 1000 kg marketable commodity[1/]

N		P		K		Mg		Ca		Na		Mn		Zn		B		Mo		Cu	
%	kg	%	kg	%	kg	%	kg	%	kg	%	kg	ppm	g	ppm	g	ppm	g	ppm	g	ppm	g
Cutting in 4th whorl																					
1.33	5.4	0.145	0.59	0.54	2.2	0.107	0.43														
Cutting in 5th whorl																					
1.21	4.9	0.117	0.47	0.47	1.9	0.097	0.39	0.49	2.0	0.026	0.11	506	204	75	30	22	9	0.66	0.3	9.1	4
Cutting in 6th whorl																					
1.13	4.6	0.110	0.44	0.47	1.9	0.092	0.37														

1/ Based on the general dry matter ratio: 404-kg/1000-kg marketable commodity.

therefore comprises stands of various structures, and the preparation of the experiment results must be done by the multiple regression method.

Table 4 shows the results of these investigations. A look at the central part of the table (diameter 10-cm, medium stem number) shows that fertilization secures a yield level about 30 percent higher than that of the nonfertilized stands (Holstener-Jørgensen 1973). This estimate is probably too low.

Figure 5 shows the development in yields in an experimental area for soils that are fertilized (hatched columns) and not fertilized (open columns). The columns in 1974 and 1976 are the yields per year back to 1972 and 1974, respectively--in the mentioned periods cutting was done only at the end of the period. The figure shows that the yield level is fairly constant at about 7 t per ha per year during the whole of the period for nonfertilized soils. For fertilized there is at the beginning a rather steep rise; and after a lapse of 5 or 6 years, the curve flattens out at about 13-14 t per ha per year or close to a redoubling of the yields. The reason for the illustrated development trend after fertilization is that several years will pass before a biomass has been built up to maintain a high level of productivity.

Fertilization experiments in *Abies nordmanniana* for production of decoration greenery have shown a similar development. Table 5 shows cutting yields from a fertilization experiment in *Abies nordmanniana* established in the spring of 1975 (Holstener-Jørgensen 1982). In 1977 there is a clear decline of excess yield with increasing quantities of fertilizers. Taken together, the yields in 1979 and 1981 seem to indicate proportionality, and the excess yields are increasing with the passage of time. It is recommended, therefore, to fertilize with the large dose; that is, 336 kg NPK per hectare per year.

Table 3--At restorative fertilization the following quantities of nutrient in kg per ton of greenery is supplied

Commercial fertilizer	N	P	K	Mg	Cu
16.5-kg nitrophoska + 36.0-kg $CA(NO_3)_2$	7.58	0.86	2.34	0.21	
33.6-kg NPK 23-3-7 with Mg + Cu	7.59	0.97	2.22	0.54	0.03

Table 4--Regression values for non-fertilized and fertilized plots of Abies nobilis

Diameter		Non-fertilized			Fertilized		
		Stem number			Stem number		
		Low	Medium	High	Low	Medium	High
cm							
5	kg[1]/	8190	9182	10173	10816	12695	14575
	rel.	100	100	100	132	138	143
10	kg.	5480	7030	8581	6277	9217	12156
	rel	100	100	100	115	131	142
15	kg	2795	4892	6989	1787	5763	9738
	rel	100	100	100	64	118	139

1/ Kg marketable greenery per hectare and year (Holstener-Jørgensen, 1973).

Table 5--A survey of the total cutting yields (two whorls per cutting) at each cutting in a fertilization experiment with Abies nordmanniana in the Grasten State forest district

Year		Control	168 kg NPK per ha and year	336 kg NPK per ha and year
1977	t/ha	11.59	13.50	14.25
	rel.	1.00	1.16	1.23
1979	t/ha	11.38	13.29	16.48
	rel.	1.00	1.17	1.45
1981	t/ha	12.65	16.38	19.38
	rel.	1.00	1.29	1.53

IMPLEMENTATION

Skovstyrelsen (1976) drew up a report recommending fertilization of older Norway spruce in areas of sandy soil in Jutland. The working party calculated the costs of various spreading methods and recommended the use of the tractor-mounted Swedish-made Moteska fertilizer distributor. In smaller areas of decoration greenery, broadcasting by hand may be relevant.

For the purpose of a statistical survey being made in the United States and covering the period July 1, 1979, to June 30, 1980, in late summer 1980 I gathered information about Danish fertilizer consumption and area fertilized during that period. It appeared that 8 700 ha were fertilized during the time period with a consumption of 713 t N, chiefly of the fertilizer type 23-3-7 with Mg and Cu. The figures cover both older Norway spruce stands, in which on an average 125 kg N per hectare was used, and older and younger decoration greenery and Christmas tree areas, in which the average consumption has been somewhat lower.

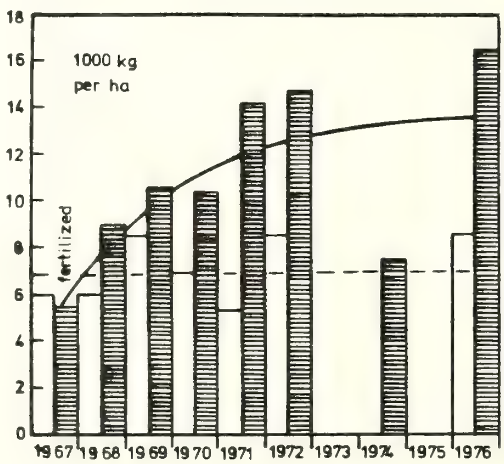

Figure 5.--The yield development in a noble fir fertilization experiment. Hatched columns = fertilized, open columns = non-fertilized.

PERSPECTIVES

We consider that the completed experimental program covers the need for fertilization experiments in Denmark. Presumably, local problems will occasionally appear, most often in connection with micronutrient deficiency. Currently, experiments are under way with Mn deficiency (Ca-induced) and Cu deficiency (lowland moor).

Greater perspectives are opened up by current and planned irrigation experiments. These experiments will help determine the production ceiling, and the extent to which irrigation will be used in future. This will result in new fertilization directions (Holstener-Jørgensen and Veracion 1978).

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CURRENT FOREST FERTILIZATION PROGRAMS
IN NEW ZEALAND

G. M. Will

ABSTRACT: In 1980 more than 26 000 ha of Pinus radiata D. Don plantations were fertilized: 7 600 ha were new plantings and 19 000 ha were established plantations. In addition, 3 900 ha of sand dunes were fertilized as part of stabilization before tree planting. Major nutrients applied were: 1 900 t of N, 1 100 t of P and 10 t of B.

Today the major programs remain similar to those of 1980 and consist of: (1) Applications of N, P, K, Mg to seedling nurseries and applications of N to marram grass on sand dune stabilization areas. (2) Hand applications of P or N and P at time of planting in the field. (3) Aerial application of P to P-deficient stands, 4 years or older, on phosphate deficient sands and clays. (4) Aerial application of N to stands on coastal sands and to recently thinned stands on volcanic ash soils. (5) Aerial application of B to stands on a range of B deficient soils in the South Island.

INTRODUCTION

Logging of the native forests that once covered much of New Zealand is being steadily reduced as resources are used up and more of the remaining areas are included in national parks and other reserves. Expanding forest industries are becoming almost totally dependent on exotic forest plantations which are already by far the major source of forest produce: out of a total land area of 27 million ha, forest plantations to date exceed 800 000 ha and are being expanded at the rate of 40 000 ha a year. These plantations are largely Pinus radiata D. Don and some of them are on infertile soils that require fertilizer before acceptably vigorous tree growth is achieved.

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Small plantings of exotic Eucalyptus spp. are also being established and many of these require fertilizer.

The application of fertilizers to New Zealand forests began in the 1950s; but it is only since 1970 that it has become a major forest operation. The area treated annually increased 10-fold in the 1970s (Will 1981).

In 1980 more than 30 000 ha received fertilizers: 7 600 ha of new plantings, 19 000 ha of established forest, and 3 900 ha of sand dunes being stabilized by the growth of marram grass (Ammophila arenaria) before tree planting. Applications of fertilizers to plantations totaled 1 900 t of N, 1 100 t of P, and 10 t of B. Small quantities of N, P, K, and Mg were used

in nurseries (Will 1981). A recent survey[1] indicates that 2 years later the use of fertilizers has increased, but only marginally. Figure 1 shows where nutrient deficiencies affect tree growth in New Zealand.

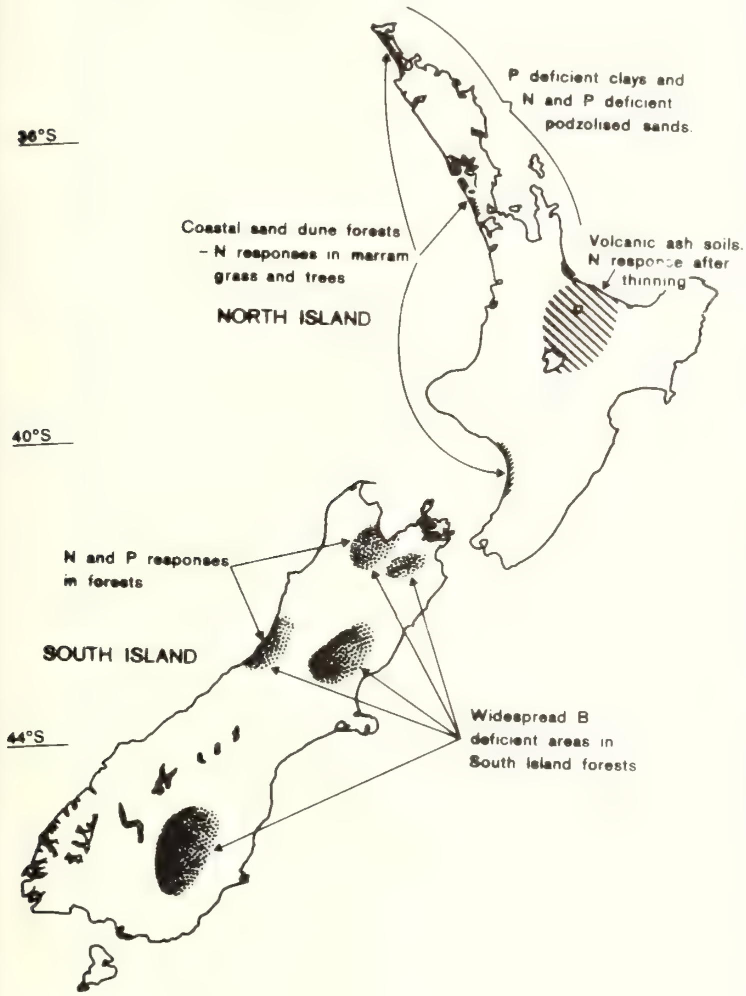

Figure 1.--Districts in New Zealand within which fertilizers are currently applied to forests. Annual rainfall in North Island forest plantations is 1 000-1 500 mm; in the South Island rainfall ranges from 3 000 mm plus on the west coast to less than 800 mm in central and eastern regions. Mean annual temperatures range from 14.5°C in the north to 10° C in the south.

Current forest fertilizer programs for <u>Pinus radiata</u> are best considered under six headings:

1. Nurseries and marram grass
2. At time of planting
3. Aerial application of P to deficient stands
4. Aerial application of N after thinning
5. Aerial application of N to forests on coastal sands
6. Aerial application of B

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[1] G. M. Will. Data on file at the Forest Research Institute, Rotorua, New Zealand.

FOREST NURSERIES AND MARRAM GRASS

Current practice in nurseries is similar to that described by Knight (1978). Before sowing, soil tests are carried out and suitable base dressings of P, K, and Mg fertilizers are applied. During the life of the tree crop in the nursery, supplementary applications of fertilizers are made, particularly during periods of maximum growth which presumably indicate periods of peak nutrient demand. Nitrogen, often along with other nutrients, is applied in a granular form between rows of seedlings and cultivated into the soil. Where unforeseen deficiencies of N or Mg become apparent, foliage sprays may be used to bring about rapid return to normal appearance and growth.

Plantings of marram grass to stabilize sand dunes are fertilized with 60 kg/ha of calcium ammonium nitrate in the spring after planting followed by a repeat application the following autumn.

FERTILIZATION AT TIME OF PLANTING

Ballard (1978) reviewed research and practice. Since that time the annual program has expanded but practices are basically similar. Currently about 7 600 ha per year are fertilized at time of planting.

On P-deficient soils (less than 9 ppm Bray-extractable P in the topsoil), 150-170 g of single superphosphate are placed in a spade slit 15 cm from trees planted 1-3 months previously. On soil types where trials have shown that responses can also be obtained to N, 85 g of diammonium phosphate (DAP) are applied. This quantity of DAP can be pressed into a convenient-sized pellet which is used when obtainable at an economical cost.

Trials are in progress with rock phosphates, broadcast and spot, applied; but it is too early to predict what practices may develop.

P-DEFICIENT STANDS

In the early 1950s, before the use of fertilizers in forests was given serious consideration, severe dieback and mortality occurred in some forests in the north of the North Island. By the mid-1950s, trials had shown that the application of superphosphate resulted in rejuvenated tree crowns and dramatically increased growth rates. Since then, superphosphate applications have become part of standard forest management in existing and newly established forests on all P-deficient soils. Currently about 10 000 ha per year of existing stands are fertilized with P.

After the year of planting, the need for P fertilizers is monitored by means of foliage analyses. Foliage samples are taken on a routine basis during February and March. These are analyzed at the Forest Research Institute; and according to percentage of P present (Will 1978),

recommendations are made that are the basis for determining priorities for fertilization later in the year. Samples taken from stands on soil types likely to be low in N are analyzed for both N and P.

The standard rate of P application when Mead and Gadgil (1978) wrote their review of research and practice was 1 250 kg/ha of single superphosphate. Since then application by fixed-wing aircraft has been replaced by application by helicopter fitted with a Decca electronic guidance system. The improved uniformity of the fertilizer spread has allowed the application rate to be decreased to 1 000 kg/ha. Further improvements in spread are anticipated as well-granulated, dust-free superphosphate becomes available; the application rate may then well be lowered to the 650 kg/ha shown by Hunter and Graham (1982) to be an economically optimum rate.

Where foliage levels of N are also low, DAP is applied at 400 kg/ha.

APPLICATION OF N AFTER THINNING

New Zealand's largest Pinus radiata forests are on the volcanic pumice plateau in the center of the North Island. These deep free-draining soils are not highly fertile by agricultural standards, but they are excellent soils for forestry and grow very high-producing stands of trees. Along with stands on some other soil types, these are not normally responsive to fertilizers; however, growth responses in the region of a 10 percent gain in basal area can be obtained when N fertilizer is applied immediately after thinning. As is so often the case in forests in many different countries, the optimum application rate of N seems to be approximately 200 kg/ha, and the period during which annual growth is increased lasts 4-6 years. Urea fertilizer is used and most of it is applied by helicopter although some ground spreading is done. Currently about 7 000 ha per year of thinned stands are fertilized with N.

APPLICATION OF N TO FORESTS ON COASTAL SANDS

Despite the addition of N from yellow lupins (Mead and Gadgil 1978), stands of Pinus radiata on recent coastal sands are frequently marginal to low in N (New Zealand Forest Service 1982). Hunter and Hoy (1983) have shown that a gain of 40 m^3/ha over 5 years (+43 percent volume increment) was achieved by applying 200 kg N ha^{-1} after thinning. A gain of 70 m^3/ha was achieved after applying 400 kg N ha^{-1} to an unthinned stand that would not otherwise have yielded a merchantable return. Management scale fertilization has recently begun, with less than 1 000 ha per year being fertilized; this area is expected to expand.

APPLICATION OF BORON FERTILIZERS

In the South Island of New Zealand there are a wide range of soils on which Pinus radiata is B deficient. Knowledge of soil types, foliage analyses, and observations of deficiency symptoms are used to plan fertilizer applications. Boron, in the form of a sodium borate fertilizer, is usually applied at the rate of approximately 8 kg/ha; in sandy soils a lower rate is used to avoid burning (toxicity). Application is usually by aircraft. On P-responsive soils borated superphosphate is applied by fixed-wing aircraft; on other soils straight boron fertilizer is applied by helicopter. Areas fertilized annually with B range from 1 000 to 2 000 ha per year.

FERTILIZATION OF EUCALYPTUS SPP

Young Eucalyptus spp. have a much higher requirement for N than does Pinus radiata. Most plantings receive 15-30 g N/seedling (usually as urea) soon after planting. Some of the largest plantings are on pumice soils, and these receive an additional 250 kg urea/ha as an aerial application at age one year.

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A REVIEW OF FOREST FERTILIZATION PROGRAMS IN AUSTRALIA

John Turner

ABSTRACT: Phosphatic fertilizers are the most commonly used fertilizers in Australian forests, and they are applied mainly to exotic conifer plantations. In 1979, approximately 26 000 ha of plantation were treated or retreated with phosphatic fertilizers, an increase of 12 000 ha since 1973. In the early 1970's, the most common fertilizer was superphosphate; however since then, there has been a greater emphasis on N-P fertilizers particularly at time of planting. Nitrogenous fertilizers (without added P) are rarely used, but they will probably increase in importance in the future with applications after thinning. Approximately 10 000 ha of conifer plantations are presently treated with micronutrient-containing fertilizers, predominately zinc and copper. More extensive problems with boron deficiency in conifer plantations are expected in the future. The differing fertilizer programs in the various States and the reasons for recent changes in practices and future trends are discussed.

INTRODUCTION

Nutritional deficiencies that could be rectified by fertilizer amendments were recognized in exotic conifers grown in Australia in the 1930's and 1940's (Kessel and Stoate 1936, Ludbrook 1939, Smith 1943, Stoate 1950, Young 1948); however, fertilizer programs have become routine only in recent years. Although initially they were aimed at overcoming obvious nutrient deficiencies and improving tree health, subsequently they have centered on further increasing productivity of existing reasonably productive sites.

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Misled by the success of *Pinus radiata* D. Don grown on apparently infertile sands in the Mount Gambier region of South Australia in the late 1800's, foresters formed the opinion that forestry (and pines in particular) "uses climate and the closed canopy and mycorrhiza to fertilize its soils: the farm fertilizer has small economic place in silviculture" (Henry 1963). So despite the clear indication of nutritional problems in the work of the early researchers, there was a marked tendency on the part of forest managers to reject nutritional explanations of poor growth in favor of those involving climate (Beuzeville 1943, Prescott and Lane-Poole 1947). Eventually the economically favorable locations of some of the poorer sites led to the development of adequate research programs which unequivocally demonstrated the lasting benefits that could be obtained by comparatively simple fertilizer amendments.

Table 1--Australian native forest areas classified according to forest types1/

Forest type	Australian State2/								
	A.C.T.	N.S.W.	N.T.	Qld.	S.A.	Tas.	Vic.	W.A.	Total
	Thousands of hectares								
Rainforest	-	300	38	1 085	-	472	-	-	1 895
Eucalypt -									
Class I	-	1 173	-	205	-	504	645	176	2 703
Class II	51	3 649	-	1 290	-	1 848	4 582	2 816	14 236
Class III	-	8 320	-	3 300	-	-	559	19	12 198
Tropical eucalypt and paperbark	-	-	2 450	4 078	-	-	-	-	6 528
Cypress pine	-	1 908	778	1 686	-	-	-	-	4 372
Total	51	15 350	3 266	11 644	-	2 824	5 786	3 011	41 932

1/ Except for Cypress pine, the native forests already or potentially have a mature height of 20 m+ (Australian Yearbook 1980).
2/ A.C.T. - Australian Capital Territory; N.S.W. - New South Wales; N.T. - Northern Territory; Qld. - Queensland; S.A. - South Australia; Tas. - Tasmania; Vic. - Victoria; W.A. - Western Australia.

Because the problems are different from one location to the next, and the forests are managed by six separate States and some private landowners, the programs that now exist differ greatly, and some of the reasons for these differences will be discussed in this paper.

FOREST AREAS IN AUSTRALIA

Australia has a total land area of about 770 million hectares which is comparable with that of continental United States (excluding Alaska); but less than 6 percent (42 million ha) of the total area can be classified as productive forest compared with the estimated 25 percent of the continental United States (F.A.O. 1974). Australian native forests classified on a broad basis (table 1) include about 2 million ha of rainforest and 3 million ha of high quality eucalypts (*Eucalyptus* spp.), but the major part of the 42 million ha is cypress pine (*Callitris* spp.) and lower to average quality eucalypt. Although many of these forests are classified as eucalypt, the large number of species and differing properties are such that throughout Australia the result is a very wide range of forest types.

Generally the native forests are managed at a low level of intensity. More intensive management, however, is directed to the plantations of both exotic and native species for reasons that are related to the higher productivity of plantations, the ability to establish them in specific locations, and the desirable properties of the wood produced. The area under plantation is approximately 750 000 ha of which 93 percent is conifers, mostly (66 percent) *P. radiata* (table 2). It is in these plantations that most of the fertilizers are used.

When the areas of planted conifers are subdivided on the basis of ownership, some of the background reasons for fertilizer usage and differences in practices become apparent. The States of Queensland and Western Australia have the lowest emphasis on planting *P. radiata*, with the former having less than 2 percent *P. radiata* in its plantation area and the latter about 60 percent (table 3). The particular climate and soils in Queensland have resulted in the planting of *Araucaria* spp. and southern pines (*P. caribaea* Morelet, *P. elliottii* Engelm., *P. taeda* L.) while Western Australia has planted *P. pinaster* Loud. in addition to *P. radiata*. In New South Wales, more than 90 percent of the 140 000 ha of plantation are *P. radiata* concentrated in large planting blocks to attract large-scale integrated industry to the resource, and until quite recently, there have been only fiscal limits on the amount of land utilized for planting. The situation in Victoria is different in that a large proportion of plantings are privately owned. South Australia has the longest plantation history because of a lack of any native forest resource and has essentially utilized all available suitable land for plantation purposes, so increased production can only be derived from greater productivity per unit area.

Table 2--Area of plantation types in Australia (1980)

Species	Area		Planting rate
	ha	percent	ha/yr
P. radiata	480 000	66.0	14 300
Other coniferous species	201 000	27.7	9 200
Eucalyptus species	42 400	5.8	1 100
Other broadleaved species	3 400	0.5	0
Total	726 800	100.0	24 600

Table 3--Australian plantation areas of conifers, June 1980

State	Government-owned		Privately owned conifer	Total conifer
	P. radiata	Total conifers		
	- - - - - - - - - -	- - - - - - - - ha	- - - - - - - - - -	- - - - - - - -
Australian Capital Territory	12 788	13 639	-	13 639
New South Wales	118 472	129 507	37 896	167 403
Northern Territory	-	1 213	2 778	3 991
Queensland	2 516	117 483 1/	30 048	147 531
South Australia	66 584	72 530	19 536	92 066
Tasmania	31 231	31 479	9 840	41 319
Victoria	78 045	82 281	76 479	158 760
Western Australia	22 250	45 650	11 171	56 821
Total	331 886	493 782	187 748 2/	681 530
Total *P. radiata*				480 146

1/ Includes Hoop, Kauri, Bunya, Slash, Loblolly, Patula, Caribaea, and Longleaf.
2/ 148 260 ha are *P. radiata*.

PLANTATION SOILS

Australian forest soils were either not claimed for agricultural usage because they had a variety of problems, and/or were geographically isolated, and/or were topographically undesirable. Phosphorus has been found to be the most widespread nutrient deficiency, particularly in the soils derived from sedimentary and intrusive parent materials. Deficiencies of boron and sulphur (in soils derived from basic extrusive and intrusive parent materials), zinc and potassium (on sands), copper (on humus podzols or coastal sands), and calcium (on soils of acid extrusive and recent sedimentary origin) have also been found. Although critically low levels of soil nitrogen are rarely found, responses to nitrogen can be obtained on most soil parent materials either in conjunction with phosphatic fertilizers at planting or as nitrogenous or mixed N-P fertilizers applied after thinning. Many of the micronutrient problems, for example copper and boron, only become apparent on some sites after growth is stimulated by more intensive silvicultural practices (including usage of N-P fertilizers or mounding); thus the necessity to relate the fertilizer form to the soil and stand condition.

The lack of a suitable uniform forest soil classification system has made it difficult to compare plantation sites within Australia. When reviewing published work and developing a basis for extrapolation of research and other data from various areas, Turner (1979) used soil parent material as a broad index for such comparisons. The categories included (a) extrusive materials, predominantly basic, (b) intrusive materials, and (c) sedimentary materials subdivided into *in situ* parent rocks, gravels, and sands. When the areas represented by these different soil parent materials were expressed as a percentage of the planted area of *P. radiata* within the various States, critical differences were apparent (fig. 1). On the basis of soil parent material, the total *P. radiata* plantation system is divided into 19 percent basic extrusive, 11 percent metamorphic, 15 percent granitic, 33 percent sedimentary and 22 percent sands. Although this type of classification system was unrefined, it indicated that New South Wales, Victoria, and Tasmania have comparable soil parent material types with basic extrusive and sedimentary rocks being dominant. South Australia is dominated by

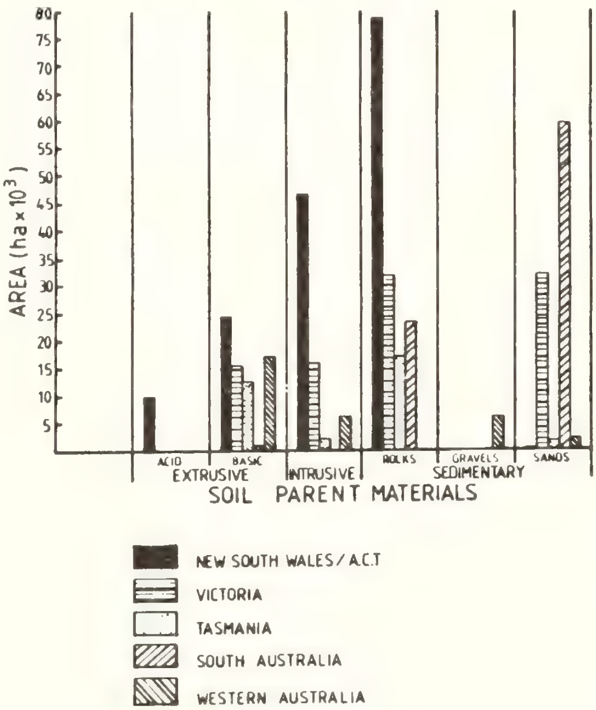

Figure 1.--Distribution of the major *P. radiata* plantations in Australia.

Table 4--Estimated total area of Australian plantations treated with phosphatic fertilizers (including NP fertilizers)1/

Australian State	Year				
	1973	1978	1979	1980	1981
	- - - - - - - -	- - - - - - - -	ha	- - - - - - - -	- - - - - - - -
Australian Capital Territory	200	300	600	900	1,000
New South Wales	450	1 200	1 250	1 500	1 800
Queensland - Govt.	6 000	9 700	9 800	5 760	6 200
- Private	1 300	800	800	800	1 200
South Australia	1 320	4 760 2/	6 270 2/	5 410 2/	6 400 2/
Tasmania	600	1 800	2 730	2 500	2 000
Victoria - Govt.	1 195	3 160	2 920	1 990	1 900
Private	2 415	1 500	1 500	750	1 000
Western Australia	400	800	1 500	1 700	1 700
Total	13 880	24 020	27 370	21 310	23 200

1/ Areas include those treated a second time as well as treatment at planting.
2/ Includes multiple treatment areas.

sands, some of which extend into Victoria, and although not included separately, Western Australia has lateritized soils not generally present in other States. Queensland was not included due to the small planted area of *P. radiata,* but plantings there are on soils derived from granitic and basic extrusive rocks. So although results from fertilizer practices can be extrapolated in general, specific practices have to be developed for local situations (for example, the differing impacts of added 9 phosphorus because of differing phosphorus fixation capacities). This exacerbates the variability between States in fertilizer practices which arise for other reasons.

PRESENT USAGE OF FERTILIZERS IN PLANTATIONS

Differences in age class distribution, planting rate, and proportion of second rotation area, together with the high degree of diversity in ownership, species, soils, and climate are of importance. In the planning of planting programs, there is a tendency to assume specific minimum levels of unit area productivity, and in order to achieve a given overall volume production, plantation areas are expanded until the target is achieved, or competition for the land becomes too great. At this stage, the relative costs and returns from continued expansion are assessed as opposed to more intensive treatment of stands. South Australia reached this point some years ago, New South Wales is just reaching it, and Western Australia is continuing to expand.

It is also necessary for a market to exist with specific features, for example pulp, particle board, sawlogs, veneer logs, or mixed products. In Australia, exotic conifers were selected for planting because of their relatively fast growth rate and specific wood properties, but in many areas a market was not immediately available. When the market consumes only part of the production, there are no real incentives for more intensive timber production programs, but when production is fully allocated, the incentives for *more intensive production are increased. For* example, South Australia has very high utilization of the forests while New South Wales is only just beginning to intensify. These two factors, land competition and market, need to be considered to understand the present fertilizer programs and to be able to predict future trends

Phosphatic Fertilizers

Phosphorus is the dominant fertilizer element applied to Australian forests. It is mostly applied as single superphosphate, sometimes with trace elements added, or mixed with nitrogenous fertilizers for use at time of planting. In 1979 about 26 000 ha were treated or retreated with phosphatic fertilizers (table 4), but in 1980 financial limitations reduced this to 19 000 ha. The areas treated in the last 3 years represent a significant increase, however, from the 13 500 ha treated in 1973, and this trend will probably continue for at least another 5 years because of the nature and extent of future planting programs. The areas treated prior to 1973 were predominantly extremely phosphorus deficient and fertilizer applications were necessary to obtain a merchantable crop. In Victoria and South Australia, the treated areas included deep sands in Queensland they included coastal quaternary deposits, and in New South Wales small areas of triassic sediments were treated. Superphosphate was the phosphatic fertilizer almost exclusively used at that time, especially since the Federal Government paid a bounty for its use.

By 1979-80, there was a reduced emphasis on the initial treatment of sites chronically deficient in phosphorus because many of the poorest areas had already been fertilized and stand health had improved. Since then, more emphasis has been

Table 5--Estimated area of coniferous plantations treated with micro-nutrient fertilizers in 1980

Australian State	Area	Micronutrient	Method of application
	ha		
Australian Capital Territory	100	Boron	Aerial application as boronated super-phosphate
New South Wales	-	-	-
Queensland	1 140	Copper	Mixed N-P fertilizers - ground applied
	570	Copper, zinc, boron	" "
South Australia	5 030 (1 400)[1/]	Copper, zinc, boron	Mixed N-P fertilizer - ground applied several times
Tasmania	-	-	-
Victoria - Govt.	565	Zinc	Zinc sulphate - aerially applied
- Private	720	Copper	Superphosphate with 1 percent copper added
Western Australia	2 420	Copper, zinc	Mixed fertilizers
Total	10 545		

1/ The net area treated is 1400 ha. 5030 ha represents the multiple treatments occurring in the schedule.

placed on retreatment of the poorer sites to maintain productivity, and on mixed fertilizers (N-P) to stimulate the somewhat better sites. The most intensive of these practices have been developed in South Australia (R. Boardman *pers. comm.*[1/]). Mixed N-P fertilizers have been used on old pasture and second rotation sites in New South Wales (Turner 1979) and the Australian Capital Territory, and on sands in Western Australia (McGrath 1979). Queensland has had a consistently high usage of phosphatic fertilizer because of the original emphasis on *P. elliotti* and the planting of extensive areas of poor soils. It has been estimated that the total quantity of phosphorus used in Australian forest in 1981 was about 1 950 t (Attiwill 1982), which when compared with the 800 t used in 1973, represents a considerable increase.

Future treatments will probably be related to more intensive second rotation establishment and a constant but small annual increase in first rotation plantation area. Further emphasis will be placed on the use of N-P fertilizers at plantation establishment (especially in conjunction with weed control) together with booster treatments of P alone or N-P treatments at a later stage in the rotation. One reason for the increased emphasis on N-P fertilizers is due to the high responses obtained in trials across all productivity classes.

Nitrogenous Fertilizers

Fertilizers containing nitrogen without added phosphorus are presently not used extensively but areas of approximately 200 ha have recently been treated after thinning. These have not been areas with obvious nutrient deficiencies but represent sites where approximately 30 percent increase in volume periodic annual increment has been obtained in experiments when nitrogen was applied after first and subsequent thinning. It *is proposed in the future to treat more extensive* areas, particularly high productivity stands to increase saw and veneer log production. This is dependent upon the availability of funds and the existence of suitable markets rather than forest stand conditions.

Under present circumstances the use of nitrogenous fertilizers will require calibration on specific sites, mainly because other nutrient deficiencies such as boron and sulphur can be induced. Surveys for foliar analysis (in particular nitrogen, phosphorus, boron, and copper) will be required until stand parameters are developed for use as indicators of nutritional status.

Potassium Fertilizers

Potassium deficiency has been reported predominantly in the privately-owned *P. radiata* plantings in Gippsland, Victoria (Raupach and Hall 1974). These sites in the past have been treated annually with potassium chloride, but they no longer appear to require such intensive treatment. Responses to potassium have been found on lateritic kraznozems and coastal sands in Queensland when treated with N-P fertilizers (D. I. Bevege *pers. comm.*[1/]) and on some sedimentary sites in Tasmania (Ellis *et al.* 1975). However, no estimates of routine requirements have been made in this paper.

1/ Boardman, R. 1980. Woods and Forests Department, South Australia.

1/ Bevege, D.I. 1980. Queensland Forestry Department, Australia.

Micronutrient Fertilizers

Approximately 10 000 ha conifer plantations are annually treated or retreated with some form of micronutrient amendment (table 5). Some of this area involves multiple treatments, for example in South Australia, and other areas include those treated with P or N-P fertilizers as shown in table 4. A range of soil types are involved for conifers with these micronutrients (Hill and Lambert 1981).

The emphasis with micronutrient treatments is presently on zinc and copper, the former being amended on sandy soils with either zinc sulphate spray (in Victoria) or mixed fertilizers (South Australia). Zinc deficiency is very easily recognized and treated (Hill and Lambert 1981) and was the first deficiency to have broad-scale fertilizer treatment carried out in Australia. Copper deficiency is found on a range of soils including sandy soils with high organic matter in Victoria, Queensland, and Western Australia and on highly improved pasture sites on basaltic soils in Victoria. Formulations of mixed fertilizers are being developed in an attempt to overcome the availability problems of copper, especially when copper is applied to humus podzols where rapid immobilization with organic matter occurs. More extensive areas, in particular former highly improved pasture sites, are expected to be treated in the future. On these sites, high growth rates may lead to deficiencies because of effects of dilution or, possibly, physiological interactions of nutrients leading to stem deformities.

Although only limited areas are presently being treated in Australia for boron deficiency, these are increasing in extent, particularly where plantings have been made on old pasture sites in New South Wales and Victoria. The total timber production on a site may not be reduced by a lack of boron, but the stand will have stem deformities such as multiple stems, thus reducing the merchantable proportion (Lambert and Turner 1977). It is expected that 500 ha of *P. radiata* will need to be treated with boron-containing fertilizers in New South Wales in 1982, and this area will continue to increase when more intensive establishment techniques are extended. The treatments include either a single tree application of borax or a broadcast treatment of boronated superphosphate on sites where phosphorus is also limiting.

DEVELOPMENT OF FERTILIZER PROGRAMMES

The range of soil types on which exotic conifer plantations have been established include those adequate for the purpose and also poor soils where it appeared to be the best way to use such land. While the necessity to fertilize these latter soils was well accepted, the instigation of fertilizer programs on the adequate sites has met with some resistance. The fertilizer programs in coniferous plantings have tended to develop chronologically in the following sequence:

1. Correction of chronic, very obvious, nutrient deficiencies--in particular, phosphorus and zinc. It is necessary to add fertilizer in order to obtain a crop.

2. Extension of the fertilizer program to the more productive areas. N-P fertilizers are used at planting, and booster P or N-P treatments are used later in the age of the stand. This form of treatment is also applied to second rotation sites.

3. Intensive management of sites with treatments including site preparation, weed control, and multiple fertilizer additions at planting plus subsequent fertilizer treatments. This form of treatment can be applied to the whole range of sites, and productivity gains are very high. A range of micronutrient deficiencies, such as boron and copper, may be induced, however, thus necessitating closer monitoring of stands and secondary treatments as necessary.

4. Fertilization of established stands to produce specific products. These treatments usually involve nitrogenous fertilizers applied after thinning, and they aim to capitalize on the high-value timber produced near the end of a rotation. This is especially the case where financial bonuses can be achieved for specific size classes.

All stages of the above sequence are being carried out in Australian forests at the present time, but where 5-10 years ago the major emphasis was on stage 1, now stages 2 and 3 are becoming increasingly important, and stage 4 is being contemplated and evaluated. The reasons for this change in emphasis include the greater competition for land and the increasing importance of second rotation plantings.

METHODS OF APPLICATION

The application of fertilizers has normally been by hand at planting and/or broadcast from fixed-wing aircraft. In Victoria, zinc sulphate is applied as a foliar spray. Hand applications involve applying a measured volume of fertilizer adjacent to the tree before, at, or within 6 months after planting. The fertilizer may be placed as a spot or band adjacent to the tree or placed in slits parallel to the rooting plane, the latter treatment providing generally better results. The aim is to supply nutrients to the developing plant without simultaneously stimulating weed growth. In many areas there is a follow-up or booster broadcast treatment at 4 to 6 years of age; that is, on these sites there will be a treatment of phosphorus or N-P fertilizer at planting followed by a booster phosphate treatment. On sandy soils in South Australia, there may be several spot treatments at varying distances from the tree to accommodate the developing root system, followed by a later age treatment. When

Table 6--Plantation areas of broadleaved species in Australia (1979)

Australian State	Government-owned		Privately-owned		Total	
	Eucalypts	Total	Eucalypts	Total	Eucalypts	Total
	- - - - - - - - - -	- - - - - - - - - -	- - - - ha - - - -	- - - - - - - - - -	- - - - - - - - - -	- - - - - - - - - -
Australian Capital Territory	-	-	-	-	-	-
New South Wales	8 556	8 556	7 034	9 352	15 590	17 908
Northern Territory	-	-	-	-	-	-
Queensland	1 623	2 095	1 262	1 353	2 885	3 451
South Australia	859	859	-	-	859	859
Tasmania	554	554	1 819	1 819	2 373	2 373
Victoria	6 903	6 975	5 497	5 497	12 400	12 922
Western Australia	8 300	8 300	-	-	8 300	8 300
Total	26 795	27 339	15 612	18 471	42 407	45 810

broadcasting phosphatic fertilizers from fixed-wing aircraft, difficulties have been experienced in that the size class distribution of granules and application rate are often uneven. In recent trials on later aged thinned stands, ammonium nitrate has been broad-cast spread from a tractor and very even cover has been obtained.

NONCONIFEROUS SPECIES

The nonconiferous species are predominently native eucalypts. Apart from extensive natural stands, there is a modest plantation program resulting in about 42 000 net-planted ha (table 6). A spot application of N-P fertilizers at planting is made in many of these plantings. In addition to plantations, there are considerable areas in which forest enrichment practices are carried out and there are also plantings on tracks and log dumps. In these cases, the fertilizer used is an N-P mix applied either as loose fertilizer or as a compressed sulphur-coated pill placed in the planting hole. The aim is to accelerate growth in the initial years to overcome weed competition. Approximately 2 600 ha are treated in this way annually.

MONITORING OF SITES

Routine monitoring programs have been set up in most States to determine both the necessity for, and the effect of, fertilizer applications. These include a combination of field growth measurements and foliar chemical analysis. The interpretation of the data thus obtained is relatively simple for phosphorus, potassium, and zinc and the procedures are inexpensive. Routine analyses however, for example for boron and sulphur are more costly and difficult to interpret. It appears that these programs will need to be extended and intensified when later age fertilization and multiple fertilizer applications become more routine.

FUTURE RESEARCH REQUIREMENTS

The Australian Forestry Council established Research Working Groups composed of researchers in specific fields from the various forestry organizations, and these Groups meet every 2 or 3 years to exchange information and review progress. The most recent recommendations from Research Working Group 3 (Soils and Nutrition), which have been included as an assessment of problem areas, indicate that the areas that should be given a high priority in future research are: (1) The limits to growth of a range of species on various sites and the optimization of productivity, particularly of *Pinus* spp. (2) Trace element problems in plantations, with particular reference to copper, boron and zinc, fertilizer form, and the inducement of deficiencies by various forest practices. (3) The role of nutrient deficiencies, such as sulphur, in increasing disease potential. (4) The delineation of a wide range of soil types and their reaction to specific fertilizer treatments. (5) Relationships between water usage and nutrients. (6) Stimulation of nitrogen-fixing species of such genera as *Acacia* and *Casuarina* to increase growth in native forests of the important timber producing species.

ACKNOWLEDGEMENTS

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FOREST FERTILIZATION PROGRAM IN JAPAN

Akira Kawana and Kikuo Haibara

ABSTRACT: This paper presents forest fertilization in Japan, it's methodology and theory. It could be said that Japan has good species of soft wood for artificial planting such as Sugi and Hinoki, and also has long history of tree plantation and forest fertilization, resulting in increased yield of wood per unit area.

INTRODUCTION

The forest land area in Japan is about 25 million ha and the area per capita is as small as 0.22ha. Forests cover about 67% of the land area and more than 9 million ha have been planted artificially. The artificial forest is 37% of the total forest area of Japan and 12% of the world artificial forest land.

The history of forest plantations is very old, and the beginning of forest industry was between 3 and 4 centuries ago. After the opening of Japan in the Meiji era, forestry technology was introduced from Germany, but the domestic forest technology was taken rather lightly. Silviculture in Germany began through natural regeneration of beech (*Fagus crenata* Bl.) and spread to softwoods, as they became more important. On the other hand, Japan has good softwood species in Sugi (*Cryptomeria japonica* D. Don), which has good wood quality and is suited for planting in Japanese hilly soil. Domestic silvicultural techniques were preferred such as those employed by Yoshino Forestry which has a long history of forest management. After the vigorous consumption of wood during and after World War II, expansive afforestation was started in the 1950's; and the forest technology, such as machinery, chemicals, and fertilizers, were introduced mainly from the United States. The Japanese technique of forestry, a compromise between Japanese and foreign styles, was then established. Accelerated tree planting continued until the 1960's.

The present state of forest fertilization in Japan was reported by Kawana (1969), and Kawana and Haibara (1981). Forest fertilization using organic fertilizers was introduced earlier in Japanese forests in the Edo era. Chemical fertilizers were already introduced in forestry in 1915 using ammonium sulphate. The research papers in this field before 1956 were presented in a bibliography by Tsutsumi *et al.* in 1958. Forest fertilization before the 1930's was mainly carried out in the infertile forest lands; and after publication of the book "The Theory of Forest Fertilization" by Kaburagi (1932), the importance of theoretical research in forest fertilization was recognized in Japan and the extension of the technology followed the proposal of Shibamoto in 1951.

The outline of the history of Japanese forest fertilization is as follows:

- 1920's Fertilizing the infertile forest lands.
- 1930's Research done on forest fertilization in infertile soil. Study of chemical composition of nutrient solution of water and sand culture of seedlings of principal tree species.
- 1940's Basic research on nutrient physiology of seedlings of principal species.
- 1950's Rational control of fertilization in tree nurseries. The establishment of fertilization techniques for young stands.

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Table 1--Classification of forest soils in Japan

Soil group	Subgroup
Podzolic soils (P)	Dry podzolic soils Wet iron podzolic soils Wet humus podzolic soils
Brown forest soils (B)	Brown forest soils Dark brown forest soils Reddish brown forest soils Yellowish brown forest soils Surface greyed brown forest soils
Red and yellow soils (RY)	Red soils Yellow soils Surface greyed red and yellow soils
Black soils (Bl)	Black soils Light colored black soils
Dark red soils (DR)	Eutric dark red soils Dystric dark red soils Volcanogenus dark red soils
Gley soils (G)	Gley Pseudogley Podzolic gley
Peaty soils (Pt)	Peat soils Muck soils Peaty podzol
Immature soils (Im)	Immature soil Eroded soil

From Forest Soil Division, 1975
Expt. St. of Forestry and Forest Products

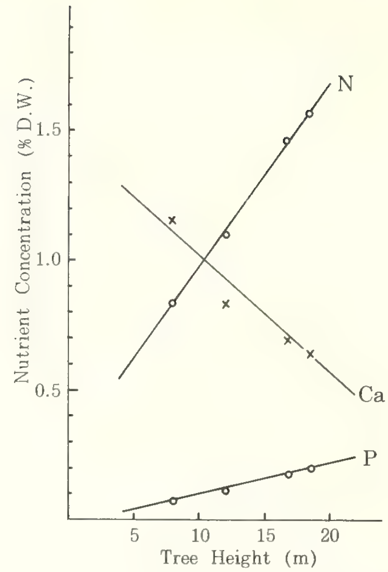

Figure 1.--Relationship between tree height and nutrient concentrations in the needles of a 40-year-old Hinoki tree (from Shibamoto and Tajima, 1961).

1960's — The establishment of chemical analysis of needles and soils for Sugi and Hinoki forests by means of nutrient diagnosis. The proposal of fertilization in the established forest.

1970's — The establishment of fertilization in the established forest and the techniques of judging the efficiency of fertilization.

1980's — Research and practices already developed include guidelines of fertilization techniques in each working system of forestry on short rotation with fertilization and nutrient balance in needles and forest soil in relation to fertilization.

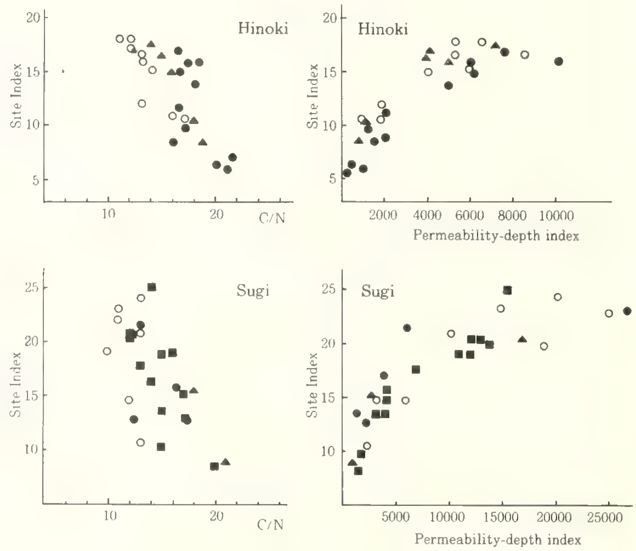

Figure 2.--Relation between C:N ratio and permeability index and site index (from Mashimo, 1960).

This paper will report on the program of forest fertilization in Japan in relation to forest soils.

FOREST SOILS IN JAPAN

Japan is situated between latitudes 24-46° N. ranging from subtropical to subarctic, with many kinds of soils. The classification of forest soils in Japan by the Forest Soil Division (1975) of the Experiment Station of Forestry and Forest Products is shown in table 1. Forest soils in Japan are developed under conditions of high rainfall. Coniferous forests in the northern area are characterized by slower decomposition of litter with leaching of base elements and iron, resulting in podzol. In contrast, hardwood forests in the warm temperate or subtropical zone have red soil and decomposition of litter is fast. The soils are rich in iron and aluminium. Brown forest soils occur between these two zones and constitute 74% of forest soils. Leaching of base elements is still high, and the soils are poor in Ca, Mg, N, and P. There are also andosol or

Table 2--Linear correlation coefficient between nutrient level of needles and soil properties of surface soil

Nutrient level of needles	Properties of soil	Linear correlation coefficient
N	N level	0.891**
	C : N	-0.907**
P	P_2O_5-t level	0.828*
	P_2O_5-org level	0.832*
	C : P_2O_5-org	-0.957**
K	N HNO_3 soluble K_2O level	0.711
Ca	Exch. CaO level	0.148
	Rate of exch. CaO saturation	0.320
Mg	Exch. MgO level	-0.405
	Rate of exch. MgO saturation	-0.323

From Kawada et al., 1973

Remarks: ** Significant r at 5% level = 0.874
* Significant r at 1% level = 0.754

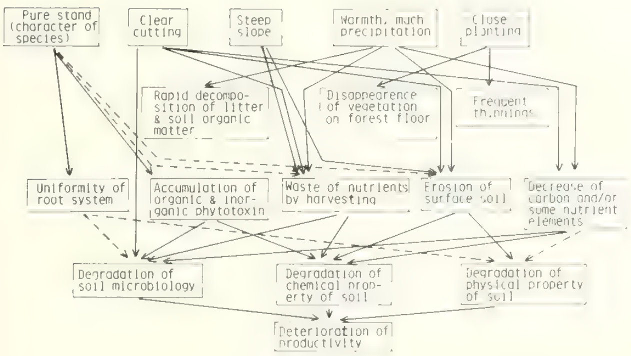

Figure 3.--Factor of deterioration of site productivity (modified from Kawana 1965 & Sugiura 1977).

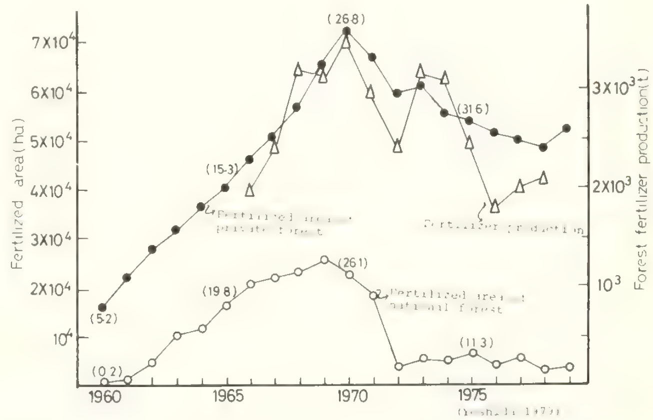

Figure 4.--Fertilized area of private and national forests and production of forest fertilizers. Figures in parentheses show the percentage of fertilized area to planting area.

black soils, which originated from volcanic ash or granite, and these make up 11% of the total soils. These soils are generally deficient in available P and N.

50% of the forest plantations are situated above 400 m elevation, and 80% are on slopes of more than 15 degrees. Precipitation is high with an average of about 1700 mm and exceeds 5000 mm in some places. Decomposition of litter is moderate in the warm moist areas, resulting in a C:N ratio of 10 to 20 in the surface soil.

Within these environmental conditions, the principal tree species used for lumber production, such as Sugi and Hinoki, show a high correlation in average tree height by age 40 with nutrient concentrations of N and P (fig. 1). There is also a high correlation in C:N ratio and permeability of surface soil with site index (fig. 2). Concentrations of N and P in the needles show a high correlation with C:N ratio and C:Org-P ratio in the forest soil (table 2).

CHARACTERISTICS OF FOREST FERTILIZATION IN JAPAN

Coniferous species such as Sugi and Hinoki provide good quality lumber in Japan. Good temperature and precipitation regimes provide for generally high growth rates. Foresters aim to accumulate more growing stock per hectare and to shorten rotations. Moreover, road and cable yarding networks are necessary for logging and transportation in the steep forest lands. Plantations are generally single species with clearcutting, harvesting, and artificial regeneration. Deterioration of productivity may occur with management as illustrated in figure 3.

In the early 1950's, Shibamoto (1951) proposed forest fertilization at the time of planting to recover soil fertility, reduce competition between seedlings and weeds, and promote crown closure. Japanese forest fertilization has been carried on to achieve these purposes since then.

Annually, the pattern of fertilized area changed as shown in figure 4. In the 1960's, the fertilized area increased in both national and private forests. It reached a peak in 1969 in national forests, when about 30% of the planted area was fertilized. The area fertilized has decreased gradually in national forests and since 1972 it

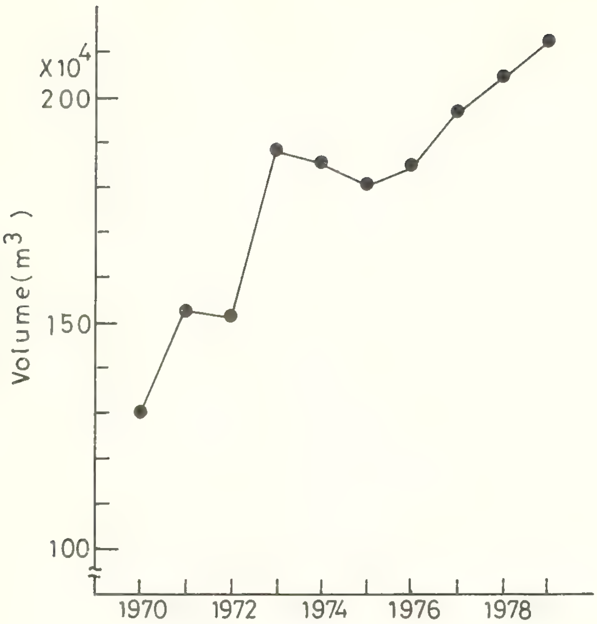

Figure 5.--Number of reports on forest fertilization in Japan.

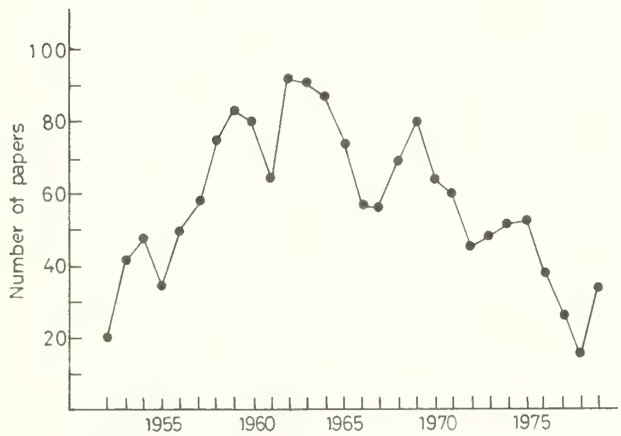

Figure 6.--Felled volume of logs for shiitake mushroom cultivation in Japan.

constitutes about 10%. The area of private forest fertilized reached a peak in 1970 when 27% of the planted area was treated. Decreases in forest fertilization have been caused by a decrease in areas regenerated, lack of labor supply in the rural areas, increasing cost of fertilizers, and the low price of domestic timber.

Research papers on forest fertilization, including nursery practices, peaked in 1962 (fig. 5) when 90 papers appeared. The number of papers has decreased, especially after 1975, not only because of a decrease in forest fertilization, but also because of better data on fertilization practices. The contents of Japanese papers also changed from reports of simple efficiency of fertilization to ecological, physiological, or new technological approaches. For example, fertilizer research on Kunugi plantation, Kunugi (Quercus acutissima Carr.), and Konara (Quercus serrata Thunb.) are

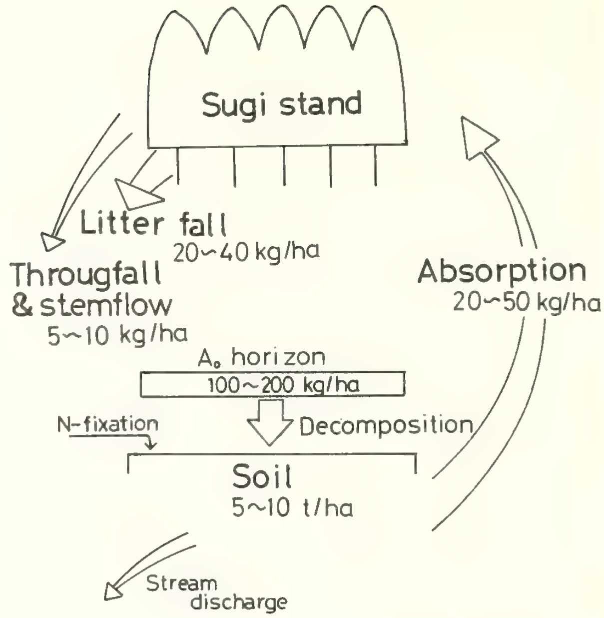

Figure 7.--Nitrogen cycle in a Sugi stand (from Kawana, 1981).

increasing because not enough logs for shiitake mushroom culture are available (fig. 6). Research is also being carried out on municipal sewage sludge, deterioration of soil fertility in the second and third rotations, and on nutrient cycling in the fertilized forest (Haibara 1980). Additional research will be necessary on slow release fertilizers, which are being developed now, and the balance of elements in foliage and soils as a result of fertilization.

FOREST FERTILIZATION PRACTICES AND PROGRAMS IN JAPAN

Forest fertilization practices must take into account physiological and ecological changes that occur in forests as they develop. Decomposition of organic matter in Japanese forests is relatively rapid. Steep slopes and high rainfall may accelerate leaching from the forest ecosystem and this is a source of concern. The Japanese forests should conserve soil nutrients under a stable cycling after crown closure (fig. 7).

Fertilization practices in Japan have three stages. The first stage is fertilization in young plantations before crown closure. The purpose is to promote rapid crown closure. Shibamoto (1951) emphasized that fertilization in young plantations reduced the degradation of soil by rapid closure of crown after planting in clearfelled areas and that it further improved soil fertility, resulting in a more stable cycling of nutrients, recovery of the environment, and reduction in the number of weedings. The idea was well received in Japanese forestry and it played a major role in forest fertilization in Japan.

The practice of fertilization in young plantations consists of a bottom dressing in the planting hole and half-circle dosage around seedlings in or on top of the soil. The soil dosage may extent to a

Table 3--Relation between foliage color symptoms at lower crown position and nutrient concentration in needles of upper part of crown

	Current year's needles			1-year-old needles		
	Green[1/]	Red-yellow	Red	Green[1/]	Red-yellow	Red
N	1.79±0.13	1.85±0.15	1.69±0.15	1.29±0.21	1.38±0.18	1.25±0.10
P	0.15±0.01	0.15±0.02	0.17±0.03	0.12±0.02	0.12±0.02	0.13±0.02
K	0.86±0.11	0.91±0.07	0.89±0.08	0.88±0.18	0.95±0.14	0.96±0.07
Ca	0.69±0.15	0.65±0.10	0.61±0.16	0.77±0.13	0.63±0.13*	0.62±0.09*
Mg	0.130±0.020	0.111±0.018*	0.093±0.022**	0.109±0.017	0.098±0.014	0.083±0.012**
N/P	11.8±1.1	12.5±1.7	10.1±1.3**	11.2±0.6	11.6±1.4	10.0±1.5*
N/K	2.12±0.27	2.05±0.22	1.93±0.10	1.51±0.24	1.47±0.26	1.31±0.16
N/Ca	2.71±0.56	2.92±0.32	2.97±0.91	1.73±0.48	2.30±0.74	2.03±0.29
N/Mg	14.0±1.9	17.1±2.6**	17.9±4.0*	12.1±3.2	14.5±3.4	15.4±2.7*
P/K	0.18±0.02	0.17±0.03	0.19±0.05	0.14±0.02	0.13±0.02	0.13±0.01
P/Ca	0.24±0.06	0.24±0.06	0.30±0.02	0.15±0.04	0.20±0.07	0.21±0.06*
P/Mg	1.20±0.20	1.37±0.19	1.78±0.30**	1.08±0.26	1.26±0.26	1.56±0.26**
K/Ca	1.33±0.47	1.43±0.24	1.57±0.50	1.18±0.38	1.53±0.32*	1.52±0.35*
K/Mg	6.74±1.49	8.44±1.77**	9.54±2.68*	8.16±2.12	10.1±3.02	11.9±2.34**
Ca/Mg	5.30±1.04	6.10±1.72	6.39±1.95	7.12±1.23	6.61±2.05	7.75±1.74

From Haibara (1980).
Remarks: ** Significant at the 1% level , * Significant at the 5% level ,
1/ Green = normal needles.

Table 4--Schedule of fertilization in a Sugi plantation

Item	Young stage (before crown closure)	Intermediate stage	Established stage (after crown closure) (period of operation)	
Stage of stand	Planting	Crown closure	Each pruning	Each thinning
Fertilization	○○○	△	○○○	○○○
Change of surface soil	Consuption of A_0-horizon and regression of A_1 horizon		Restoration of A_0 and A_1 horizon	
Object of fertilization	Promotion of survival, vigor, growth and crown closure and enrichment of soil		Promotion of growth and crown closure after pruning and thinning, rapid recovery from wounds due to pruning	

Remarks: Open circle: time of fertilization, Open triangle: regulation of nutrient balance.

depth of 5 cm where the root system easily reaches. A few years after planting, the half-circle application expands to encompass the growth of branches. Fertilizer is applied annually for 3 years. The rate of the first year is N 10 g, P_2O_5 5 g, and K_2O 5 g per seedling. The amount increases by 20% each year for 2 years.

The second stage of fertilization is carried out at crown closure as suggested by Haibara (1980). Japanese forest soils are poor in many cases in cations (such as Ca and Mg) and the N-P-K fertilization results in an imbalance between Ca, Mg, and N, P, K in the soil or plant tissue. Mg deficiency may occur frequently (table 3). As lower branches begin to die when the crown closes, translocation of nutrients is accelerated and used in height growth. N, P, and K contents of applied fertilizer are reduced at this stage and Ca or Mg may be added.

In the third stage, fertilizer is applied to established forests as proposed by Kawana (1960). This increases growth of the trees and makes for rapid recovery of crown closure after opening by pruning or thinning. Fertilization after pruning will not only accelerate the growth rate of trees but also promote early recovery from pruning

Table 5--Working system for a short rotation in a Sugi forest, University Forest of Tokyo University of Agriculture and Technology

Stand age	Amount of fertilizer kg/ha	Treatment	Density No./ha	Clear length m
1	N-P-K (N: 40)	Planting and weeding	4500	
2	N-P-K (N: 50)	Weeding		
3	N-P-K (N: 60)	Weeding		
4	N-P-K (N:100)	Weeding		
5	Ca: 200 kg and Mg : 50 kg per ha	Pruning		1.5
6				
7	N-P-K (N:100)	Pruning		3.0
8				
9	N-P-K (N:150)	Thinning	3000	
10		Pruning		4.5
11				
12		Pruning		6.0
13	N-P-K (N:150)	Thinning	2000	
14	N-P-K (N:100)			
15	N-P-K (N: 50)			

From Haibara 1980.
Remarks: Amounts of fertilizers are calculated conveniently by N for N-P-K fertilizer (20:10:10).

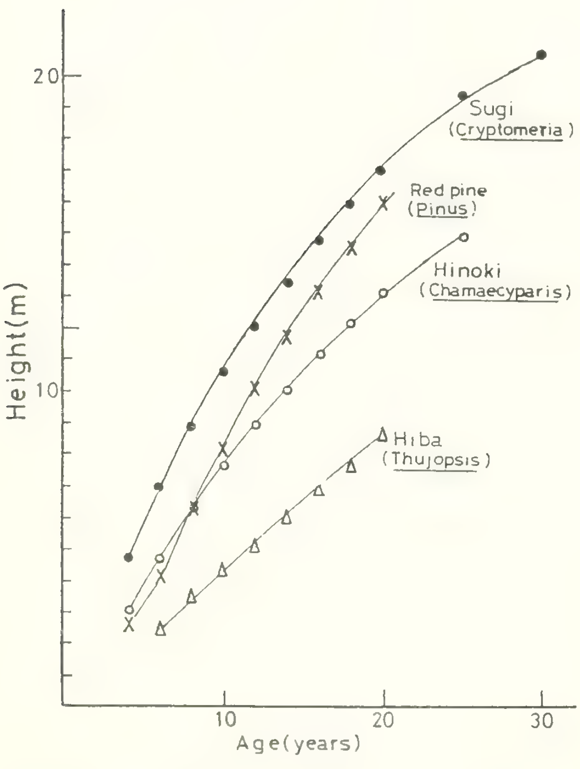

Figure 8.--Ideal height growth curve of fertilized trees in an intensively managed plantation based on the data obtained from the Annual Forest Fertilization Contest in Japan.

Table 6--Amounts of fertilizer recommended for various species of seedlings at the time of planting

Species	N	P_2O_5	K_2O
	- g/seedling -		
Sugi (Cryptomeria)	8-12	5-7	5-7
Hinoki (Chamaecyparis)	8-10	5-6	5-6
Japanese red pine	6-8	4-6	4-5
Japanese larch	10-14	7-8	5-8
Todomatsu (Abies)	8-12	5-7	5-7
Hardwoods	10-14	7-8	5-8
Poplar	24-40	16-28	12-34
Green manure trees	3-6	6-12	5-10

From Shibamoto (1961).

Table 7--Amount of fertilizer recommended for a Sugi established plantation

	N	P_2O_5	K_2O
	- kg/ha -		
1st year	100-150	50-75	50-75
2d year	50-100	25-50	25-50
3d year	50-100	25-50	25-50

From Kawana (1965) and Tsutsumi (1971).

wounds. As pruning deposits branches and needles with a high C:N ratio on the soil bed, the addition alleviates any induced N deficiency and accelerates decomposition. Fertilization after thinning shortens the subsequent interval of thinnings. Usually fertilization in this stage is carried out at three consecutive times to obtain a high level of nutrient concentration in the needles. Three hundred kg/ha of Nitrogen, 150 of K_2O and P_2O_5 per ha are applied over the 3 years. Tsutsumi (1971) said that a final fertilization between 7 and 8 years before clearcutting increased tapering grade and resulted in a better return on the investment.

A sample schedule for fertilizing is shown in table 4. The forest of Tokyo University of Agriculture and Technology reforests and fertilizes 3 ha every year. The schedule is shown in table 5. This scheme will cover a period of 30 years with the expected size of standard trees at the final cutting of 30-cm diameter at breast height (d.b.h.) and 20 m in height. The stand will have 900/ha trees with a volume of 660 m^3. Thinnings begin at the 17th year with a thinning cycle of 5 years. Fertilization rates will be 100 kg/ha of N and 50 kg/ha of P_2O_5 and K_2O each year for 3 years after each thinning.

The standard rates of fertilizers for young and established forests recommended by the Forest Fertilization Society of Japan is shown in tables 6 and 7. Height growth curves of fertilized forests were computed from data from the annual national contest in forest fertilization (fig. 8).

Table 8--Program of short rotation forest practices compiled by the Extension Committee of the Forest Fertilization Society of Japan

Age	Height	D.b.h.	Density	Stem volume	Tending	Amount of fertilizer
	m	cm	No./ha	m^3/ha		kg/ha
1	1.0		4000		Planting and weeding	N: 30
2	1.8				Weeding	N: 40
3	2.6				Weeding	
4	3.4				Weeding	N: 60
5	4.2	5.0	3000		Weeding	
6	5.0	6.2	2700		Salvage cutting	
7	5.7	7.2			Pruning (1.5 m from the ground)	N: 60
11	8.4	11.1			Pruning (1.5 m to 3.0 m)	N: 80
14	10.2	13.8	1800	170	Thinning (70 m^3/ha)	
15	10.8	14.7			Pruning (3.0 m to 5.0 m)	N:100
18	12.5	17.4	1250	210	Thinning (80 m^3/ha)	
19	13.0	18.2				N:150
24	15.5	22.0	900	270	Thinning (100 m^3/ha)	
25	16.0	22.7				N:200
30	18.1	25.7		430		
33	19.3	27.2	900	520		

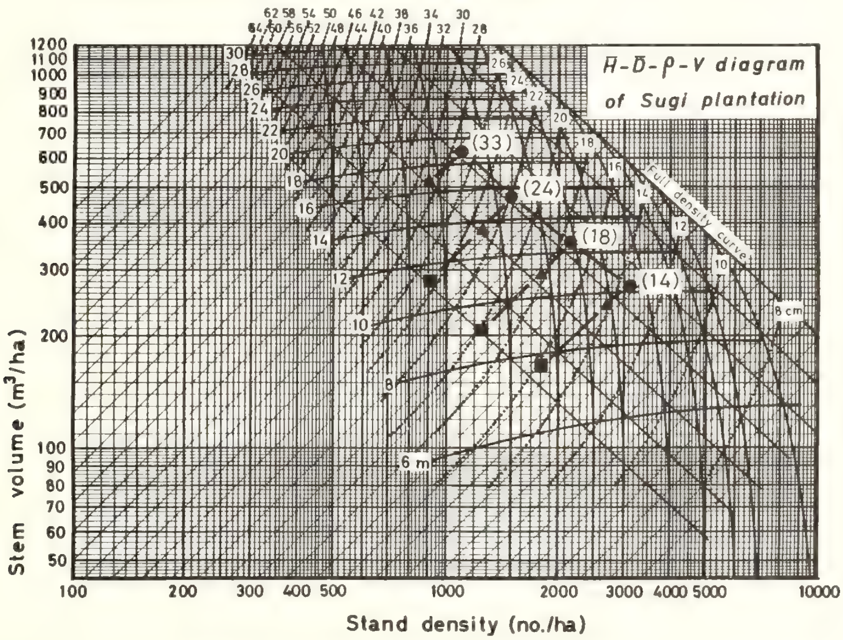

Figure 9.--$\bar{H}$-$\bar{D}$-ρ-V diagram forecasting stand growth of a Sugi plantation.

Curves of thick, solid lines at 6 m, 8, 10, ---, 30 are equivalent height curves. Straight, thin, solid lines of 45 degrees show that stand volume is proportional to stand density when mean height ($\bar{H}$) and mean d.b.h. ($\bar{D}$) are fixed. These thin, solid lines are named the volume guidelines, corresponding to actual stand density. Curves of dotted lines at 8 cm, 10, 12, ---, 64 are equivalent d.b.h. curves drawn through all height classes. Straight, thin, solid lines parallel to the full-density line are the standard growth guidelines for estimation of stand growth below maximum density. The curves of broken lines that approach the full-density line are the guidelines for estimation of stand growth at maximum density. The open-grown stands have smaller actual density than the density of the dot marked with $\bar{H}$ and d.b.h., and the maximum density stands have actual density equal to the density of the dot marked with $\bar{H}$ and $\bar{D}$.

Numbers in parentheses show the stand age of thinnings in table 8. Heavy dot denotes value of mean height and d.b.h. of stand, showing the situation of maximum density. Moving the dot along the volume guideline until the corresponding actual density is reached (as shown by heavy triangular marking on diagram) the value on the stem volume axis, represents the stem volume per ha. Heavy square represents tree number after thinning.

Future growth rates are modeled from these data. Correlation of stand density and growth of forest trees were developed from stand density control diagrams (Ando, 1968) and the $\bar{H}$-$\bar{D}$-ρ-V diagram (fig. 9) (Aiba, 1977). From these it was possible to estimate stumpage volume, thinned volume, and growth rate of trees after thinning.

Programs (table 8) for treatment or cultural operations in fertilized forest was worked out by the extension committee of the Forest Fertilization Society of Japan using the $\bar{H}$-$\bar{D}$-ρ-V diagram (see fig. 9). Four thousand trees per ha are planted and fertilization occurs eight times in a rotation. At 6 years, trees are reduced to 2700 trees/ha. The first thinning occurs at the 14th year when 900 trees/ha are removed. The average size of remaining trees is 13.8-cm d.b.h. and 10.2 m in height. The volume of thinned logs is about 70 m^3/ha. Another thinning will occur at the age of 18, leaving a stand with an average height of 12.5 m, 17.4-cm d.b.h. and 1250 trees/ha. The calculated volume of thinned logs will be 90 m^3. Finally, the last thinning will be done at the 24th year leaving 350 trees/ha and 100 m^3 as volume of thinned logs. The final clearcut is at age 33 when the average height is 19 m and average d.b.h. is 27-cm with a volume of 520 m^3/ha.

CONCLUSION

Japan has about 10 million ha of plantations which represent more than 10% of world's artificial forest land. Because these plantations are principally Sugi and Hinoki forests, a great deal of growth data is available. The survey and classification of forest soils are well developed, and suitable tree species can be selected for planting in several regions based on soils. Site index is known for most areas and a density control system for both tree species in artificial forests has been developed for each particular region.

A forest fertilization program is carried out based on the above facts. The goal is to keep soil properties in a better condition for easy absorption of nutrients by forest trees after the treatments. Weeding and thinning must be carried out in relation to the Japanese forest ecological characteristics to provide for the most efficient and cost effective program.

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FOREST FERTILIZATION IN THE PACIFIC NORTHWEST:
RESULTS OF THE REGIONAL FOREST NUTRITION RESEARCH PROJECT

C. E. Peterson, Jr., and S. P. Gessel

ABSTRACT: The Regional Forest Nutrition Research Project is a major source for urea-N response in thinned and unthinned stands of second-growth Douglas-fir. Response to 224 kg N/ha and 448 kg N/ha appears to last seven or eight years after initial application, and in unthinned stands, this is inversely related to site index. Ammonium nitrate is a promising alternative to urea as an N source.

INTRODUCTION

The Regional Forest Nutrition Research Project (RFNRP) was established in 1969 following recommendations from the Northwest Forest Soils Council for more regional forest fertilization information. Although very little was known about the growth response process, enough information had been gathered to establish that nitrogen is the major growth-limiting nutrient in the Pacific Northwest and that a designed study of regional coverage was needed (Gessel et al. 1969). The region of interest was that area bounded by the Pacific Ocean and the Cascade Range in Washington and Oregon (fig. 1).

Figure 1. Regional coverage of Pacific Northwest by RFNRP fertilizer trials.

The original design entailed sampling young second-growth Douglas-fir (Pseudotsuga menziesii [Mirb.] Franco) and western hemlock (Tsuga heterophylla [Raf.] Sarg.) forests over a 6-year period with a final report to be presented to

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cooperators (western hemlock results will not be discussed in this paper). Fertilizer trials were established in western Washington and western Oregon (fig. 2) on various soils to incorporate an array of stand ages and site indices. Because of the magnitude of this endeavor, it took 2 years (1969-1970) to establish trials in unthinned stands and 2 more years (1971-1972) to complete the design in thinned stands. RFNRP progress reports have been published on an annual or biennial basis since the inception of the cooperative. When the last Biennial Report (RFNRP Staff 1980) was published, approximately 2,000 research plots (including several pilot studies) had been established. The RFNRP results which we are presenting are drawn largely from analyses completed for the recent Biennial Report (RFNRP Staff 1982), and apply only to Douglas-fir volume growth.

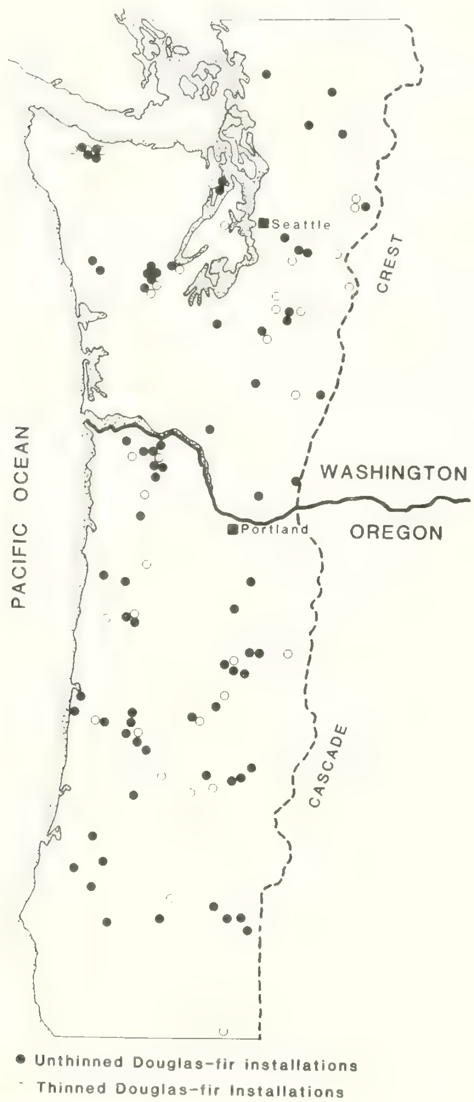

Figure 2. Distribution of Douglas-fir installations.

CURRENT STATUS

Estimating Average Regional Response

A regression model with both classification and continuous independent variables was used for estimating growth. Continuous covariates included stand age, site index, and basal area stocking. Level of N-application entered the model as a classification (dummy) variable. The response variable was the increase in growth rate due to fertilizer:

$$\text{Response} = \left[\begin{array}{l}\text{Growth rate}\\ \text{in treated}\\ \text{stands}\end{array}\right] \text{ minus } \left[\begin{array}{l}\text{Growth rate}\\ \text{as in an}\\ \text{untreated}\\ \text{stand}\end{array}\right]$$

The methodology for this analysis has been previously covered by Turnbull and Peterson (1976) and so will not be elaborated on. The same methodology is followed for estimating basal area response and volume response in both unthinned and thinned stands.

Total volume (minimum diameter at breast height = 1.55 inches = 3.75 cm, including top and stump) was estimated using tarif samples (Turnbull et al. 1972). Results presented here are based on volume growth and expressed as total periodic annual increment (p.a.i.). Because total p.a.i. was unaffected by trees growing into the 4-cm diameter class, the differences between gross and net increment reflect mortality. Mortality was detected in the unthinned stands and increased slightly with respective levels of nitrogen application. No differential mortality due to fertilizer was detected in p.a.i. of thinned stands.

Experimental Design

The experimental design chosen at the outset of the project was a randomized complete block with each block represented by a field installation. Each installation has at least

- 2 plots--no fertilizer (controls)
- 2 plots--224 kilograms of nitrogen per hectare
- 2 plots--448 kilograms of nitrogen per hectare

and each plot analyzed has a minimum area of 0.04 hectares. Thus, blocks are replicated across the region and also contain additional information on variation within blocks. The target stands of interest were young second-growth stands of unmanaged Douglas-fir. Well-stocked (85-120 percent "normal" according to McArdle and Meyer (1930)) stands were purposively chosen as candidate areas and arrayed into classes of breast height age and site index.

To ensure adequate physiographic coverage, the region was stratified into relatively homogeneous provinces similar to those used by Franklin and Dyrness (1973). Within each province, installations were located at random from an array of unthinned stands meeting the descriptive

criteria. Establishment of Douglas-fir field trials has proceeded as follows since 1969:

1969-1970--95 installations, unthinned and well-stocked; and
1971-1972--35 installations, thinned to 60 percent basal area.

The original data ranges of age and site index were supplemented in 1975.

The descriptive criteria and sampling process used for the original installations were also employed for these supplemental installations. Additional treatments were added in replicate to each block as time and area (of homogeneous stand) permitted. The treatments included urea vs. ammonium nitrate comparisons on unthinned stands (11 installations) and delayed (2 years) fertilizing on thinned stands (3 installations), as well as comparisons of response estimates between thinned and unthinned plots within the same area (12 installations).

The data base for current results ranges from 10 to 50 years initial breast height age and site classes I-IV (King 1966). Analyses are based on stands comprised of at least 80 percent basal area stocking of Douglas-fir. Statistical tests were made at the 5 percent probability level. Across all sites and ages (regional average), average growth rate of fertilized stands was significantly greater than average growth rate of unfertilized stands.

Volume Response in Unthinned Stands

We have measured and analyzed 10 years of growth data following initial fertilization in unthinned stands. An inverse relationship of response and site index was significant through the first 6 years only. Ten-year p.a.i. significantly increased 2.8 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ (12 percent) from 224 kg N/ha and 3.5 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ (15 percent) from 448 kg N/ha.

Because our remeasurements are scheduled every 2 years, we also analyzed each 2-year period separately in order to evaluate duration of response. Significant responses were found for both N-levels in each 2-year period, excepting the last (fifth 2-year period). Thus, the aforementioned gain from fertilizer over 10 years includes no real response from the ninth and tenth growing seasons. For this reason and for ease of comparison with response in thinned stands, only 8-year response is presented.

Gross response (fig. 3) is 3.0 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ (13 percent) for 224 kg N/ha and 4.0 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ (17 percent) for 448 kg N/ha. The additional 1.0 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ (4 percent) response from 448N over 224N is significant. Net responses of 2.1 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ (11 percent) and 2.5 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ (13 percent) for respective N-levels were not significantly different from each other.

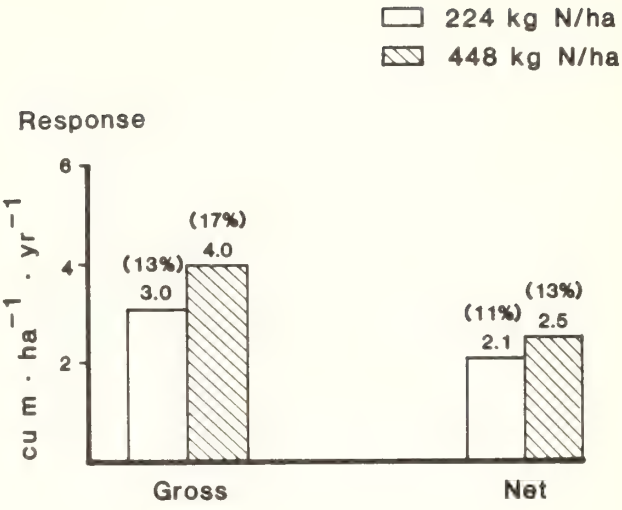

Figure 3. Average response first 8 years for unthinned Douglas-fir stands.

The 8-year estimates reflect growth response to urea as a nitrogen source. We also have 4-year growth response results from 11 installations (established in 1975 in stands of site class IV) that compare urea (224 kg N/ha and 448 kg N/ha) and ammonium nitrate (224 kg N/ha). Urea application rates of 224 kg N/ha and 448 kg N/ha have increased volume p.a.i. by 34 percent and 46 percent respectively (although this is higher response than the regional response over all sites, it is not unlike the 4-year regional response for stands of low site quality). Response to ammonium nitrate at 224 kg N/ha, however, equaled response to urea at 448 kg N/ha. We found these results to be most encouraging, especially because the success of ammonium nitrate trials on N-deficient stands has been demonstrated elsewhere (Malm and Möller 1975).

Volume Response in Thinned Stands

Response in thinned stands is significant in all four 2-year growth periods following initial application of fertilizer.

Figure 4 depicts gross and net response for 8 years following initial N-application. Gross volume response in p.a.i. over 8 years is 4 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ (20 percent) to 224 kg N/ha and 4.7 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ (23 percent) to 448 kg N/ha. These two response estimates are not significantly different from each other. Also, net and gross responses do not differ significantly as we have experienced little or no effect of mortality on p.a.i. in the thinned stands.

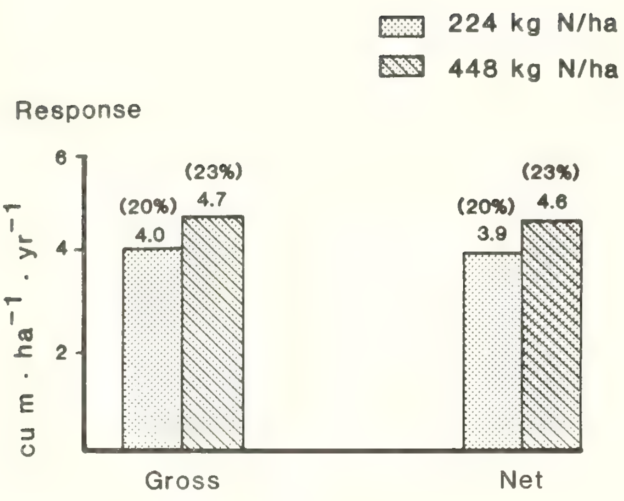

Figure 4. Average response first 8 years for thinned Douglas-fir stands.

MAJOR FINDINGS

Eight-Year Response

Volume response of all stands treated with one application of urea represents a significant increase over p.a.i. of unfertilized stands.

Site Index

Volume response in unthinned stands shows a significant inverse relationship with site index over the first 6 years, beyond which the general trend seems to appear but was no longer significant. Response in thinned stands was not related to site index.

N-Levels

The 448N and 224N responses were not significantly different for either gross or net p.a.i. in thinned stands. Response to 448N was significantly higher than response to 224N, for gross p.a.i. only, in unthinned stands.

Duration

Response to urea appears to last about seven or eight growing seasons beyond initial application.

Mortality

Mortality induced by one application of urea could reduce total potential response in unthinned stands (greater reduction from 448N) but appears to have no real impact in thinned stands for either N-level.

N-Source

Ammonium nitrate shows great promise as an alternative to urea. Average 4-year responses from 224 kg N ammonium nitrate and 448 kg N urea in unthinned stands were the same.

FUTURE DIRECTION OF RESEARCH

Low-Stocked Stands

In our analyses thus far, we have approached thinned and unthinned stands as two separate entities. That is to say, we consider thinning (or lack thereof) as an initial stand condition and fertilizer as the only treatment. We have not attempted to isolate, for example, a thinning effect and/or a thinned [X] fertilizer interaction (i.e., a possible synergistic effect), and for good reason. One criterion in originally selecting stands for fertilizer trials was that they be well-stocked. From a sampling perspective, the unthinned data base represents a population with a narrow range of high stocking. The thinned data base represents a quite different population with a narrow range of "artificially" low stocking. Consequently, it would be hazardous at best to combine the two samples without additional data from stands of "natural" low stocking.

One of our recent efforts has been to bridge these two stocking conditions with establishment of fertilizer trials in Douglas-fir stands that are naturally low stocked (i.e., no mechanical thinning). These trials should be a valuable addition to an already extensive data base. The ensuing information on growth and response should provide a link between response estimates from our earlier trials in thinned and unthinned stands. Accordingly, we should have better information on interactions of response with stand variables (e.g., stocking) and might also be closer to estimating thinning effects and/or synergistic effects.

The Third Forest

Old-growth timber is nearly gone in the Pacific Northwest and in many areas second-growth timber has also been harvested, bringing about what has been termed the "Third Forest." The management practice commonly used in these stands is a precommercial thinning at 10-15 years total age, to some specified level of stocking (number of trees per hectare). The effects of fertilizer applications (beneficial or otherwise) on such stands are, however, unknown. Therefore, along with new trials in naturally low-stocked Douglas-fir, RFNRP has also established several installations in young widely spaced plantations. Young (5-8 years breast height age) stands were precommercially thinned to approximately 750 trees per ha. One-half of the plots were left as controls and the other half received 224 kg N/ha. Growth data on those tests are not available yet.

Microsite Information

Our average estimate of response applies to a region covering western Washington and western Oregon. As with any estimate of growth increment, it is accompanied by a substantial amount of variation. Stand variables such as site index and stocking have limited capacity for explaining response variation. The extremes of variation include stands that respond much more than expected and stands that respond much less than expected. We can provide an estimate of average response over a range of low to high response across western Washington and Oregon. Advising a landowner or manager what specific response to expect for a given forest area is more difficult, however, because the project was designed to provide only regional averages, and the model contains this large unexplained variation.

In the past, because of the relatively low cost of fertilizer and generally good growth response to fertilizer, landowners have not always used fertilizer in the most efficient manner (i.e., applied fertilizer to stands that are potentially high responders). Scarcity of funds for forestry investments and increasing costs of materials have accentuated the need for more efficient, site-specific fertilizer prescriptions. The project is reacting to this need by expending considerably more research effort on soils and foliar analysis to explain variation in response. The primary goal is to identify predictive variables that significantly reduce the current body of unexplained variation in response. If that attempt is successful, then we can do a better job of site-specific estimation to improve selection of stands for response to fertilizer.

Additional information from soils and foliar analyses might also help to monitor in-place fertilizer trials (i.e., effects of fertilizer on nutrient balance and levels, pest and disease incidence, etc.). Monitoring will become increasingly important with multiple applications of fertilizer to a stand over time. Feedback of information could not only help refine growth and response projections but might also alter subsequent fertilizer prescriptions for the stand.

Nitrogen Source and Other Elements

We are obviously interested in continued comparisons of ammonium nitrate and urea, based on encouraging results to date. We have also established pilot studies involving application of additional (to nitrogen) elements such as phosphorus and sulfur. Some of these tests have been previously reported (Gessel et al. 1979). In addition, we are also testing nitrogen sources that have been made less soluble either through coatings or mixtures of urea formaldehyde.

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ADVANCES IN FOREST FERTILIZATION ON THE SOUTHEASTERN COASTAL PLAIN

N. B. Comerford, R. F. Fisher and W.L. Pritchett

ABSTRACT: CRIFF has contributed to research in forest soils and forest fertilization for the past 15 years. Due to this work, and work of others, recommendations for fertilizing young and established stands have been developed. Young stands on poorly drained savanna soils should be fertilized with either P or N and P in rates of about 50 kg/ha for each element. The optimum time for fertilizing young pine is between planting and late spring of the same year. Soil grouping and soil analysis have been helpful in identifying P deficient soils. If extractable P is < 1 ppm in the subsoil the probability for a response is large. Sources of P are best chosen on the details of material cost and application cost. Established stand fertilization can provide large long term gains in volume yield. The nutrient elements used and the nature of the response is site dependent. Foliar analysis, as currently used, has limited success in predicting fertilizer response. Response within soil groups is also variable.

In 1967 Cooperative Research in Forest Fertilization (CRIFF) became the first industry-university sponsored fertilizer cooperative in the United States. Over the past 15 years CRIFF has been a leader in the development of soil management practices and fertilization recommendations for southern pine forests. In 1967-1968, operational fertilization in the South was minimal. Since then, fertilization of forested lands has increased steadily principally due to an increase in knowledge of the growth benefits derived from fertilization (fig. 1). The work of CRIFF and the North Carolina State University Fertilization Cooperative, along with forest industry research is primarily responsible for the increased use of fertilizers in the forests of the South.

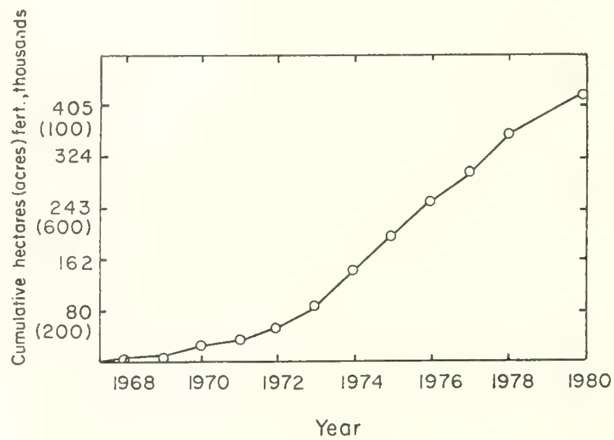

Figure 1. Area of pine forest fertilized in the Southeastern United States: 1968-1980 (from Pritchett and Comerford, 1981).

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CRIFF has been involved with both basic research in tree nutrition and soil dynamics, and applied investigations of problems associated with fertilization. These endeavors have led to research on not only fertilization, but many aspects of soil management and soil-fertilization interactions. Studies have been installed using a variety of commercial species (Table 1) including slash pine (Pinus elliottii Engelm var. elliottii), loblolly pine (Pinus taeda L.), longleaf pine (Pinus palustris Mill) sand pine (Pinus clausa Chapm.) and a number of hardwoods.

Table 1. Distribution of active CRIFF fertilization tests by species.

Slash pine only	Loblolly pine only	Slash-Loblolly	Other Species
- - - - - -	- - - - - - %	- - - - - -	- - - - - -
70	18	6	6

The purpose of this manuscript is to review current fertilizer recommendations and discuss current and future needs in fertilization research. The framework for discussing these recommendations are the two common opportunities for fertilization in the South: at time of planting and during mid-rotation to late rotation. Experience has shown that fertilization is a site-specific operation, so a brief introduction to major soil types of the southeastern coastal plain should help readers appreciate the following discussion of fertilization.

Soils of the southeastern coastal plain display a wide range of physical and chemical properties. One aspect common to the majority of these soils is an inherently infertile sandy to sandy loam cap of varying thickness. These coastal plain soils have been divided by the CRIFF program into eight major soil groups (Table 2). The groups are useful in that they combine soils of similar physical properties and provide a common ground for the discussion of forest management operations.

FERTILIZATION AT PLANTING

Not only is a significant treatment response required when fertilizing during planting, but this response must last for at least 18-30 years. CRIFF has approached the problem of fertilization at time of planting by attempting to answer the following questions.

(1) Which nutrients need be applied? A variety of elements have been tested across a range of coastal plain soils. Response to virtually all elements has been recorded, yet only a few trends are consistent. Nitrogen (N) alone is normally not beneficial to recently planted young pines. Phosphorus (P) provides the most universal growth response at this early age. In very P

Table 2. CRIFF soil groups (from Fisher and Garbett, 1980)

Soil group	Internal drainage	Diagnostic criteria	Taxonomic equivalents	Representative Series
A(fine-textured savanna soils)	Very poorly to somewhat poorly drained	No spodic horizon; argillic within 50 cm.	Typic and Plinthic Aquults	Portsmouth-Bladen
B(coarse-textured savanna soils)	Very poorly to somewhat poorly drained	No spodic horizon; argillic below 50 cm.	Arenic and Grossarenic Aquults, Aquents and Aquepts	Rutlege-Plummer
C(ultic flatwoods soils)	Very poorly to somewhat	Spodic and argillic	Ultic Aquods and Humods	Mascotte
D(typic flatwoods soils	Poorly to moderately well drained	Spodic but no argillic horizon	Typic, Aeric, and Arenic Aquods and Humods	Ridgeland-Leon
E(fine-textured upland soils)	Moderately well to well drained	No spodic horizon; argillic within 50 cm.	Typic and Plinthic Udults	Goldsboro-Norfolk
F(coarse-textured upland soils	Moderately well to well drained	No spodic horizon; argillic below 50 cm.	Arenic and Grossarenic Udults, Umbrepts & Ochrepts	Blanton-Orsino
G(dry sands)	Somewhat excessively to excessively drained	No spodic horizon; argillic may or may not be present	Psamments	Lakeland-Eustis

deficient areas, P is the difference between a commercial stand and no stand at all. When N and P are used together, N sometimes produces an additional growth response. The occurrence of this extra growth appears to be correlated to CRIFF soil groups (Table 2). Nitrogen and P together seem to produce a volume that is greater than or equal to P alone on B and C soils; equal to P alone on F soils; and equal or less than P alone on A and D soils. Specific reasons for these trends are not apparent.

Fertilizing with essential elements other than N and P shows potential. Again, this tends to be site specific. Soils of groups A, B, and C have exhibited the largest growth responses to potassium (K) and micronutrients additions once N and P are provided in sufficient quantities (Table 3). Fertilization with K and micronutrients is not recommended at this time, because we do not know what rate of K or combination of micronutrients produces the greatest yield increases.

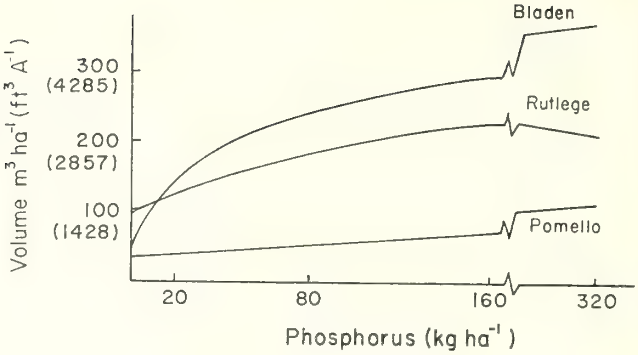

Figure 2. Volume growth response of sites on CRIFF soil groups A (Bladen), B (Rutlege) and D (Pomello) to various rates of P addition at time of planting.

Table 3. Volume gains due to potassium and micronutrients applications on CRIFF soil groups A, B, and C.

	Soil Group A & B 2/		Soil Group C 2/	
Response 1/	80kg K/ha	50kg FTE 3// ha	80 kg K/A	50kg FTE/ha
ft^3/A/yr	15 - 20	20	15 - 20	25
m^3/ha/yr	1.1 - 1.4	1.4	1.1 - 1.4	1.8

1/ Response in addition to response from 80 kg P/ha and 80 kg N/ha. Data from CRIFF A series test.

2/ Only A, B, and C soils that produced a response are used in estimates.

3/ FTE = Fritted Trace Elements 503

(2) What fertilizer rates and sources should be used? As already mentioned, information on K and micronutrient rates is lacking. However, 17 to 20 year volume yields from rate tests of P on a range of soils are available (fig. 2). On the average, 45-55 kg P/ha is the recommended rate, but on highly deficient group A and some group B soils as little as 20-30 kg P/ha produces a large growth response that lasts the entire 20 to 25 year rotation. The recommended rate of N (~40-50 kg N/ha) is based on the observation that young plantations do not have the ability to utilize a large quantity of N. Also, even though vigorous competing vegetation remains a problem for seedling estabishment, stimulating additional weed growth with high rates of N is unwise.

Phosphorus fertilizer source has been a major concern. A recent analysis (Pritchett and Comerford 1982) revealed that the long-term response to equal rates of ordinary superphosphate and ground rock phosphate was similar. Additional CRIFF tests indicate that, as a general rule, P source should be chosen based on the cost of the material and its application, not on its solubility. An exception may be where soil pH is relatively high and extractable aluminum (Al) is extremely high (greater than 1000 ppm Melich #1 extractable Al), in which case ground rock phosphate is the preferred source. An analysis of the use of urea, urea formaldehyde, sulfur-coated urea, ammonium sulfate, and sodium nitrate has shown that all sources elicit similar growth responses (Fisher and Pritchett 1982). Diammonium phosphate is a convenient form in which to apply the recommended rates of both N and P.

(3) What sites should be fertilized? Choosing sites to fertilize can be accomplished using soil groups and/or soil analysis. CRIFF soil groups have proven useful in recommending fertilizer treatments for yound stands. Not all soils of the coastal plain are deficient nor do they provide a long-term response to fertilization.

Stands on soil groups A and B provide the most consistent response to P fertilization (fig. 3a). Sites on soil group C may produce significant responses, but over all sites the magnitude of the response averages less than $1.5\ m^3.ha^{-1}.yr^{-1}$ and its range includes zero response. Other soil groups generally do not respond, although individual sites occasionally have produced acceptable growth responses. When fertilizing by soil group, only soil groups A and B are candidates for treatment. Within these soil groups, those sites with subsoils having a pH near neutral or above may not give a long-term response.

Table 4. Percentage of tests correctly classified as to response potential using the two extractable P values from one, two, or three soil depths (from Comerford and Fisher 1982).

Sample depths	Correct classification			
	8 yrs		12 yrs	
cm	DA-P 1/	NH_4OAc 2/-P	DA-P	NH_4OAc
	- - - - - - - - - % - - - - - - - - -			
0-20	32	68	47	60
0-20, 20-40	55	77	53	67
0-20, 20-40, 40-60	95	77	73	67

1/ 0.05 N HCl + 0.025 N H_2SO_4 extraction.

2/ NH_4OAc (pH 4.8) extraction.

Soil analysis has been another useful tool for recommending fertilization. Soil critical levels for extractable P were recently evaluated. When surface soil analyses alone were used, a very poor prediction of long-term response resulted (table 4). Ability to determine P deficiency improved when extractable P to a depth of 60 cm was used (table 4). Combining extractable P with an index of the aerated rooting zone also shows potential for predicting a fertilizer response (table 5).

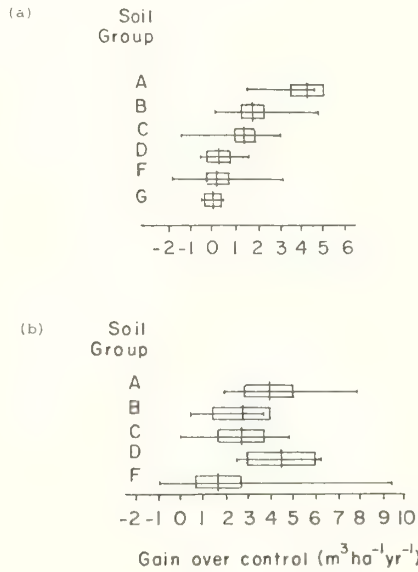

Figure 3. Eight-year mean, standard error (box) and range (horizontal line) of annual advantage over the controls for slash pine fertilized with (a) 80 kg P/ha at time of planting and (b) 200 kg N/ha and 50 kg P/ha at mid-rotation (from Kushla and Fisher, 1980).

Table 5. Percentage correct classification of response potential of tests of using extractable P from various depths and other soil variables in combination (from Comerford and Fisher 1982).

Soil variables	Correct classification 8 yrs	12 yrs
	- - - - percent	- - - -
DA-P 1/ (0-20 cm), DC 2/	73	80
NH_4OAc-P 3/ (0-20 cm), DC	73	73
DA-P (0-20 cm, 20-40 cm), DF 4/	82	73
NH_4OAc-P (0-20 cm, 20-40 cm), DC	95	80
DA-P (0-20 cm, 20-40 cm), DC	95	73
NH_4OAc-P (0-20 cm, 20-40 cm), DC	95	93

1/ 0.05 N HCl + 0.025 N H_2SO_4 extraction.
2/ DC = drainage class
3/ NH_4OAc-P (pH = 4.8) extraction
4/ DF = depth to spodic, argillic, or mottles.

A proper set of diagnostic tools that effectively discriminated responsive sites would result in significant volume gains from fertilization (table 6). If sites responsive to P could be identified, average responses to P might not increase but the number of hectares available for productive fertilization would.

Table 6. Potential gains from fertilizing young pine 1/

	P only 2/	Best Treatment 3/
	$m^3\ ha^{-1}\ yr^{-1}$ ($ft^3\ A^{-1}\ yr^{-1}$)	
Responsive soils	3.1 (44)	3.5 (50)
	65 4/	72
A & B soils only	3.3 (47)	5.7 (82)
	87	152

1/ Based on 17 CRIFF A series tests. Only sites with response 1.4 $m^3\ ha^{-1}\ yr^{-1}$ considered.
2/ 90 kg P/ha.
3/ Best combination of N, P, K and micronutrients.
4/ Percent increase over unfertilized increment.

The largest potential for increasing yield with micronutrients appears to exist on soil groups A and B (table 6). Adequate diagnostic techniques must be developed before micronutrient fertilization can be recommended.

(4) When should fertilizers be applied? One of the interesting aspects of fertilizing young trees is the timing of the fertilization. Results show that timing of fertilization is not as crucial when P alone is applied as when both N and P are used. Optimum time to fertilize is between planting time and late spring of the same year (fig. 4).

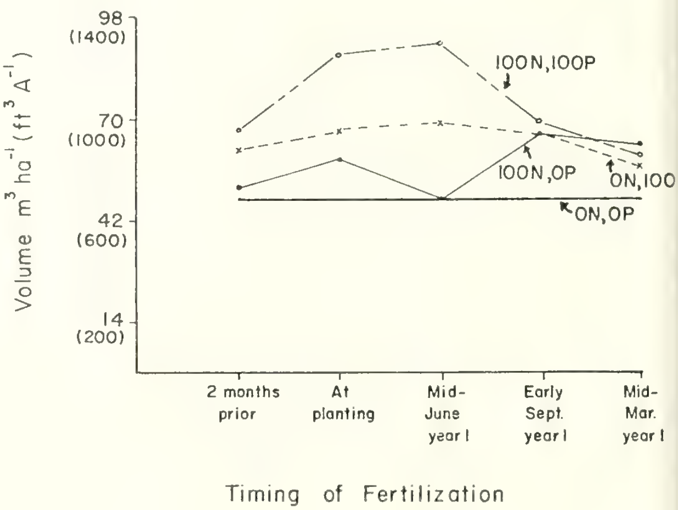

Figure 4. Effect of timing of fertilization on growth response to nitrogen and phosphorus fertilizer additions.

(5) Where should fertilizers be placed? Tests investigating the placement of fertilizers are inconclusive at this time. It appears that spot placement, banding, or broadcasting of fertilizers have approximately the same effect on yield at the end of a rotation.

Table 7. Summary of recommendations for fertilizing young pine plantations.

Topic	Recommendation
Nutrient to use	P; or N and P
Amounts of nutrients	50 kg P/A; or 40-50 kg N/A and 50 kg P/A
Sources of nutrients	RP, CSP, and DAP[1] based on cost of fertilizer and application
Sites to fertilize	CRIFF soil groups A and B; or somewhat poorly drained or wetter with subsoil (20-60 cm depth) that has $\leq$ 1 ppm double acid extractable P.
Fertilizer placement	Broadcast or band
Fertilizer application	Between planting and early summer of first year; the closer to early summer the better the response.

[1]RP = rock phosphate, CSP = concentrated superphosphate, DAP = diammonium phosphate.

A summary of CRIFF recommendations for fertilizing young pine is contained in table 7.

MID -TO LATE ROTATION FERTILIZATION

The second opportunity to fertilize a site is after the stand has established itself and dominates the site. This typically occurs in southern pines at 8 to 15 years of age. An obvious advantage of this later fertilization is that the cost of fertilizing does not have to be carried for the entire rotation. To deal with fertilization of established stands, CRIFF has attempted to answer the following questions.

(1) Which nutrients need be applied? Growth response to N, P, or N plus P is related to soil groups (fig. 5). The common nutrients or nutrient combinations giving significant responses across all soil groups are N and N plus P. Phosphorus alone commonly does not elicit a response. Exceptions are soil groups A and B that have not been fertilized at time of planting. On these soils, P alone outproduces or equals N alone. Nitrogen plus P is the optimum combination on all soils, particularly when a 5-year response is considered (fig. 5).

The small amount of research that has dealt with use of K and micronutrients indicates that K can be a crucial element in determining the growth rate on certain sites. To date, however, not enough information is available to adequately assess the usefulness of K on a wide variety of soils.

(2) What fertilizer rates and sources should be used? Test series were established in 1968-1969 and 1974 using different rates of N. In the earlier tests the slope of the rate of N vs. an 8-year growth curve decreased most between 100 and 200 kg N/ha (fig. 6), suggesting that a rate of approximately 150 kg N/ha might be biologically optimal. The 1974 test showed little if any decrease in the curve's slope between 100 and 200 kg N/ha, suggesting that a rate closer to 200 kg N/ha might be warranted. Based on these data, fertilization with 150-200 kg N/ha is recommended. The rate of phosphorus to be used in established stands has been inferred from the previously discussed research on young pine which suggested that an application of 45-55 kg P/ha is optimum.

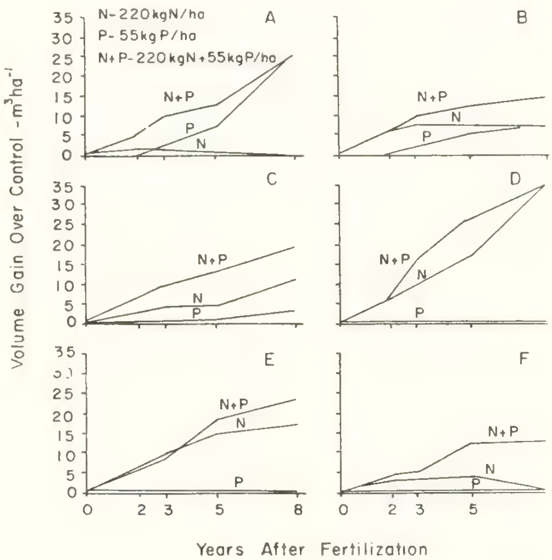

Figure 5. Response of slash pine by soil group to applications of 220 kg N/ha + 55 kg P/ha (from Fisher and Garbett, 1980).

Sources of N, including urea, urea formaldehyde, ammonium sulfate, and ammonium nitrate, were tested on pole-sized stands across a range of soils (Fisher and Pritchett, 1982). There was no advantage of one source of N over another. Therefore, the cost of material and the application are the main concerns in choosing an N fertilizer source.

(3) What sites should be fertilized? Both CRIFF soil groups and foliar analyses are currently recommended as methods for determining potentially responsive sites. At present, however, both techniques have limited usefulness.

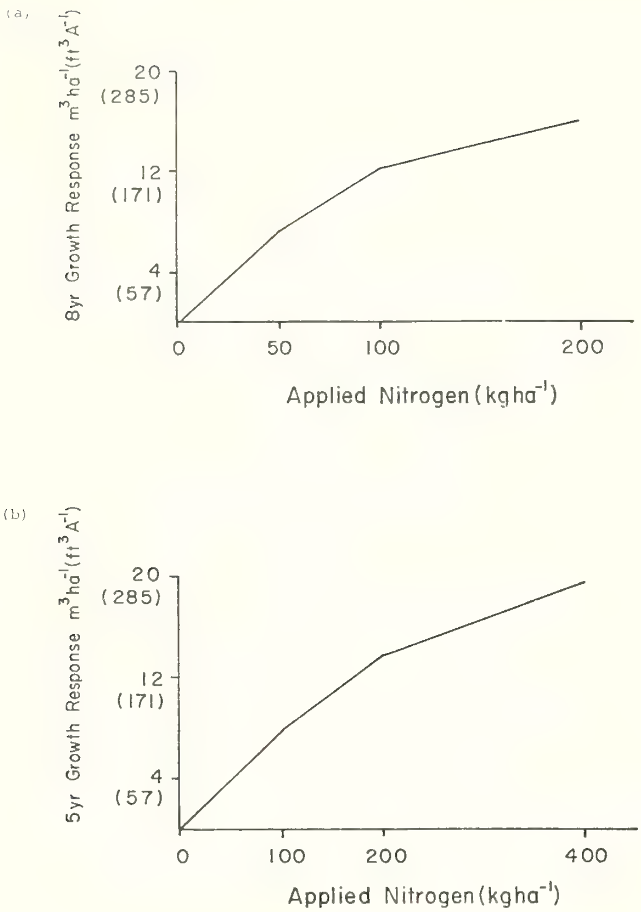

Figure 6. (a) Eight-year volume response of a 1968 trial and (b) five-year response of a 1974 trial of fertilizing established stands with varying rates of nitrogen.

Soil groupings (fig. 3b) emphasize the fact that fertilizer response within a soil group is quite variable. Only sites in soil groups A and D have shown consistently high responses. The variability of response found within a soil group is best demonstrated by soil group E (fig. 3b). Although mean response is 1.6 m^3 ha^{-1} yr^{-1}, response ranges from -1 m^3 ha^{-1} yr^{-1} to 9.5 m^3 ha^{-1} yr^{-1}. Although CRIFF soil groups make broad divisions between responsive and nonresponsive sites, they need to be refined to increase their usefulness.

Foliar analysis also has its limitations. Current critical foliar levels for N and P in slash pine are 0.9-1.0% and 0.08-0.09%, respectively. Preliminary analysis of existing data suggests that ones ability to accurately predict a fertilizer response using these levels is suspect. CRIFF is currently involved in a project to quantify sampling variability of foliar tissue to establish better guidelines for sampling and interpretation. CRIFF expects to establish foliar recommendations based on nutrient ratios or a combination of foliar levels and other factors in the near future.

A summary of CRIFF mid-rotation fertilization recommendations are provided in Table 8.

Table 8. Summary of recommendations for fertilizing established pine plantations.

Topic	Recommendation
Nutrients to us	N; or N and P (P with soil group A and B if previously unfertilized)
Amounts of nutrients	150-200 kg N/ha; or 150-200 kg N/ha and 45-55 kg P/ha
Sources of nutrients	Based on cost of material and application
Sites to fertilize	Do not fertilize excessively drained sands

(4) <u>What is the nature of the response</u>? Until several years ago the major concern of southeastern coastal plain timber producers was the production of pulp. With an increasing interest in solid wood products the distribution of volume response within the stand has become important.

The potential volume gains from fertilization have already been presented (fig. 3b). CRIFF is investigating the effect of fertilization on diameter distributions and volume distributions by diameter class. Rate of growth of individual trees, though stimulated by fertilization, increases in proportion to their prefertilization growth rate. This results in the majority of the volume accumulating in the larger trees (fig. 7).

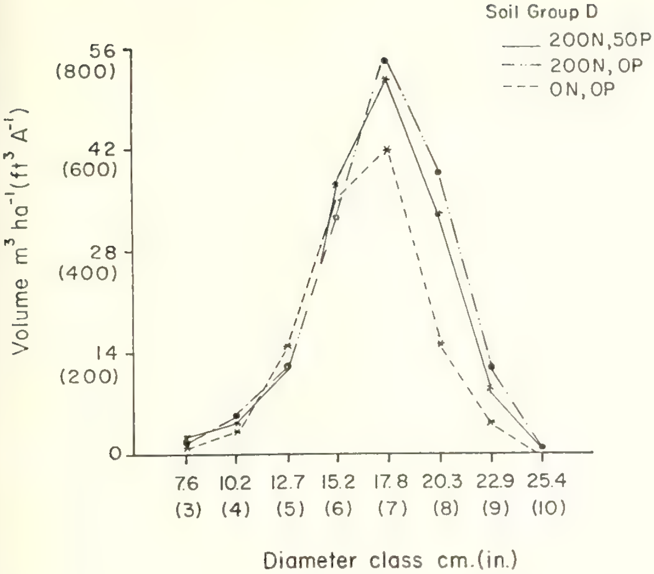

Figure 7A. Volume distribution by diameter class eight years after fertilization with 200 kg N/ha or 200 kg N/ha and 50 kg P/ha on responsive CRIFF soil group D.

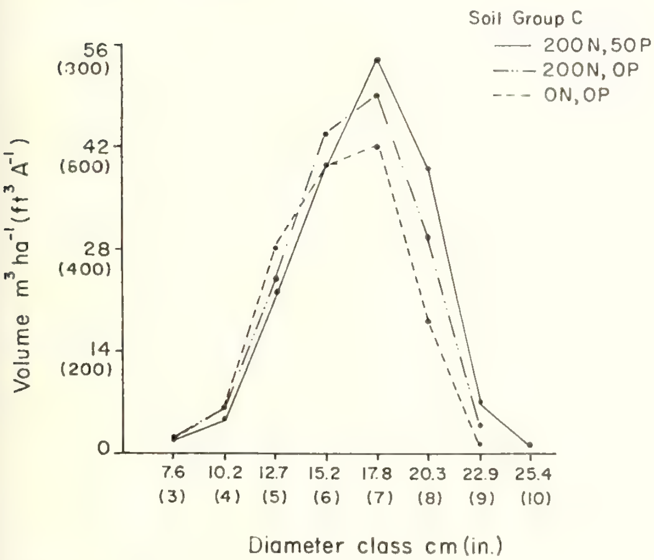

Figure 7B. Volume distribution by diameter class eight years after fertilization with 200 kg N/ha or 200 kg N/ha and 50 kg P/ha on a responsive CRIFF soil group C.

OTHER RESEARCH TOPICS IN CRIFF

Information from many large and small scale applied tests has been synthesized to produce CRIFF fertilizer recommendations. A variety of other tests have considered the interaction of feritlization with forest management operations; and graduate students, post-doctorate fellows, and visiting scientists have explored reasons that explain results from applied field test trials. A list of past and active field tests is provided in table 9 for the interested reader.

Table 9. Titles of past and current research projects of the CRIFF program.

Uniform Fertilizer Experiments on Young Pine
Uniform Fertilizer Experiments on Established Stands
1974 Uniform Fertilizer Experiments on Established Stands
P Experiments on Young Stands
P Fertilization of pine on wet sites
P Fertilization of Young Slash and Loblolly Plantations
N and P Fertilization of Young Slash and Loblolly Plantations
Evaluation of N Sources for Established Pine Forests
Effects of Fertilization on the Expression of Dominance
Herbicide and Fertilization on the Expression of Dominance
Herbicide and Fertilizer Effects on Planted Pine
Liming Forest Soils
Micronutrient Fertilization of Young Pine
P Sources of Varying Solubility
Fertilizer Placement for Young Pine Plantations
Site Preparation vs. Fertilization of Pine
Soluable P and NP sources
Timing of Fertilizer Application in Young Pine Plantations
Evaluation of Granular Ground Rock Phosphate
Potassium Fertilizer Application in Young Pine Plantations
The Effects of Burning on Fertilizer Effectiveness
Fertilization of Hardwood Plantations
Thinning and Fertilization of Established Slash Pine Stands
Species Selection vs. Fertilization of Southern Pine
Species Selection vs. Fertilization of Southern Pine
An Investigation of Seasonal, Geographical and Annual Variation in Slash Pine Foliar Nutrient Concentration.

DIRECTION OF CRIFF RESEARCH

The degree of sophistication of forest fertilization on the southeastern coastal plain has increased steadily since the late 1960's, but many questions remain unanswered. Over the next decade CRIFF will cover a wide variety of topics pertinent to the operational use of fertilizer and the need to increase site productivity. Some of the current and future projects for CRIFF include:

(1) Development and testing of diagnostic procedures for the determination of fertilizer response. Soil groupings can be refined or altered to properly reflect the growth response to fertilization. Foliar and soil chemical analyses require considerable refinement to be useful in accurately predicting fertilizer response. Techniques utilizing site and stand conditions as well as the balance of elements in the foliage are being investigated. The proper depth of soil sampling and timing of foliar sampling are also under study.

(2) Determination of the role of K, sulphur (S) and micronutrients in stand nutrition.

(3) Investigation of the interaction between fertilization and factors such as pests, genotype, planting density and soluble salt effects on moisture relations.

(4) Investigation of the potential of multiple fertilizations to maximize wood production.

(5) Development of methods to ensure the efficient use of fertilizer materials.

We anticipate CRIFF will remain a leader in the development of fertilization practices for the forestry community and will increase its efforts in the area of site productivity and soil management research.

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NUTRITIONAL MANAGEMENT OF LOBLOLLY PINE STANDS: A STATUS REPORT OF THE NORTH CAROLINA STATE FOREST FERTILIZATION COOPERATIVE

H. Lee Allen and Howard W. Duzan, Jr.

ABSTRACT: The programs of the North Carolina State Forest Fertilization Cooperative are briefly reviewed. Efforts to quantify response of loblolly pine stands to fertilization have shown that the presence or absence of volume response may not be indicative of a stand's responsiveness to fertilization. Fertilization has been found to affect stand structure, including diameter distribution characteristics, patterns of tree mortality, and height growth. Quantification of changes in these stand attributes provides for better evaluation of the economic value of fertilizer response and supports the concept that fertilization accelerates stand development. Efforts are now in progress to develop an integrated program in forest stand nutritional management.

INTRODUCTION

Loblolly pine (Pinus taeda L.) is one of the most important commercial tree species in the United States. Its range extends from the eastern shore of Maryland south to Georgia, and west to eastern Texas and Arkansas. Loblolly pine occurs naturally and has been planted across a range of soil types ranging from very poorly drained histisols, poorly to well-drained ultisols and alfisols, and excessively drained entisols.

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The North Carolina State Forest Fertilization Cooperative (NCSFFC) was established in 1969 with the objective of examining the feasibility of increasing wood production of loblolly pine by fertilization. Since its inception, the cooperative's research responsibilities have been divided between industry and the university--a system that has resulted in a very productive relationship. Industrial cooperators have the responsibility for installing, maintaining, and measuring field trials on their own lands. The university's responsibilities include development and coordination of uniform field trials and the subsequent analysis, interpretation, and publication of the results.

During the initial stages of our program, emphasis was placed on the establishment of regional field trials to address basic questions

such as elements, sources, rates and timing of fertilization, and delineation of responsive sites. The cooperative focused primarily on nitrogen fertilization in established stands to avoid duplicating phosphorus fertilization research being conducted by the Cooperative Research in Forest Fertilization (CRIFF) program at the University of Florida. During the past 12 years, 350 replicated field trials have been established over a range of stand, site, and soil conditions representative of the cooperators' land. Of these 350 trials, over 180 are presently active. These trials are part of 11 major regionwide studies.

CURRENT STATUS

Volume Response

Analyses of data from the cooperative's early regionwide studies indicated that many loblolly pine stands were quite responsive to fertilization, especially nitrogen fertilization (Ballard 1981a and 1981b, Haines et al. 1976) (table 1). Response to phosphorus alone was limited to lower Coastal Plain sites; however, a combination of nitrogen and phosphorus was superior to either element applied alone on the Coastal Plain provinces (table 1). These analyses revealed that, although loblolly pine stands on the average were highly responsive to fertilization, there was a considerable degree of variation in volume response (table 1) and that differences in initial stand density and volume and the variability of mortality following treatment often masked treatment effects. Volume gains following fertilization in overstocked stands were often reduced by mortality of suppressed trees (Haines et al. 1976). The importance of stocking in determining volume response has also been recognized by other workers (Malac 1967, Wells et al. 1976).

Table 1--Five-year volume response to fertilization in semi-mature and mature loblolly pine stands

Fertilization Treatment	- - - - Mean Response[1/] LCP	UCP	P	- - - - Range
- - kg/ha - -	- - - - - - m^3/ha			- - - - - - - -
112N	10	13	18	-27 to 47
56P	9	2	5	-34 to 49
112N-56P	19	16	17	-30 to 52
112N-56P-56K	17	18	21	-26 to 61

1/ LCP = Lower Coastal Plain (24 studies)
UCP = Upper Coastal Plain (28 studies)
P = Piedmont (49 studies)

Analyses also revealed that either ammonium nitrate nitrate or urea were equally effective as sources of nitrogen; however, maximum responses were observed when nitrogen fertilizers were applied in either spring or fall. Summer applications resulted in a decrease in response on a number of sites (Ballard 1981a). Analyses of nitrogen rate data indicated the optimum rate for volume response was achieved with 150-200 kg N/ha and showed little variation between sites (Ballard (Ballard 1981b). As expected, the optimum rate economically increased as the value of the harvested wood increased.

Modeling Volume Response

Use of a variety of statistical techniques to eliminate eliminate as many as possible of the factors confounding the response to fertilizer has become a common practice in the analysis of fertilizer trial data. Our approach to the analysis of fertilizer trial data has taken a different direction. If these confounding factors are important enough to influence response, then we believe it is important to understand them (Duzan et al. 1982). Through modeling techniques, we have sought to explain how response is influenced by stand parameters in conjunction with site, soil, and nutritional characteristics. In all of our models for established stands (Ballard and Lea 1981, Duzan and Allen 1981, Duzan et al. 1982) and those of others (Strand and DeBell 1981, Wells et al. 1976), a measure of stand density has always been the variable most strongly correlated with response. Only after accounting for the influence of stand density on response have other site and nutritional variables entered into these models.

Site index is a composite measure of the potential productivity of a particular site, reflecting physical and chemical soil properties as well as climate. Depending on the characteristics of the data set and other variables introduced into the model, response has been related positively (Duzan et al. 1982) or inversely (Ballard and Lea 1981, Duzan and Allen 1981) to site index. These findings are not surprising, given the range of site, soil, and climatic conditions covered by our field trials and the possibility that moisture (both excesses and deficits), phosphorus, or nitrogen may limit growth.

In one modeling effort (Ballard and Lea 1981), several site, soil, and foliar variables were available to enhance the predictive ability of the model and also to clarify the relationship between volume response and N-status of a site. A simplified representation of this model is given in figure 1. Our modeling efforts at this point suggest:

1. Volume response is maximized at a moderate stand density; however, near optimal responses can be obtained across a broad range of stand densities (20-30 m^2/ha).

2. Response is inversely related to site index if site index is indicative of the N-status of a stand; however, response appears to be directly related to site index if site index is indicative of other factors such as phosphorus nutrition or moisture relationships.

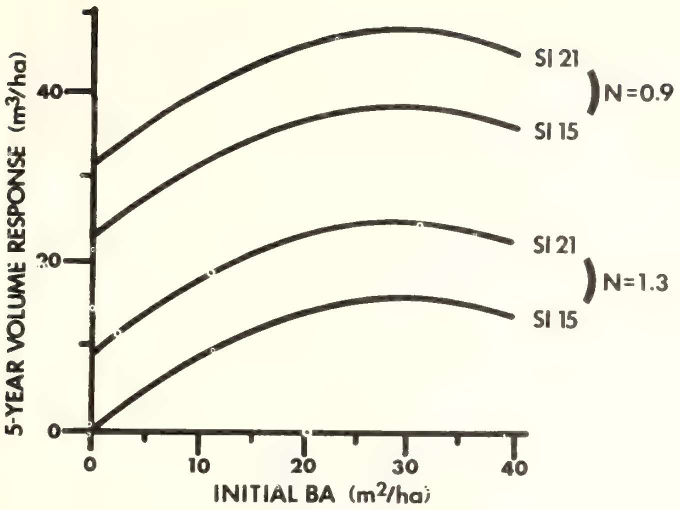

Figure 1.--Response model for nitrogen fertilization (112 kg N/ha) for non-thinned loblolly pine stands using initial basal area, site index (25 years), and foliar nitrogen concentration as predictor variables.

In the model by Ballard and Lea (fig. 1), foliar nitrogen is indicative of the nitrogen nutritional status of a site; and site index, with its nitrogen nutrition component removed, probably reflects a site's moisture and/or phosphorus status.

3. Because our models generally account for less than 50 percent of the variation associated with response, they are useful in predicting average response for a given set of stand and site conditions but not response for a particular site. This weakness results from our inability to accurately assess the nitrogen status of a particular stand and its relationship with other growth limiting factors.

The relationship between volume response and basal area appears biologically reasonable. Understocked stands will not have the "capital" on which to build response (Ballard and Lea 1981) or the "storage" capacity available within tree tissues to recirculate the applied nitrogen and thus maximize response (Miller 1981).

Volume response in overstocked stands is generally reduced because mortality of smaller trees offsets volume gains of larger trees (Rogers 1978). Consideration of the two mechanisms proposed for nitrogen response--increased photosynthetic efficiency and crown expansion (Brix and Ebell 1969, Keller 1973, Miller and Miller 1976)--has led to the suggestion that overstocked stands are less responsive to fertilizer application than stands that are not fully stocked (Tamm 1979). Overstocked stands have less opportunity for crown expansion; consequently, response may be attributed primarily to increases in photosynthetic efficiency. This theory may be true if response is viewed in the narrow sense of increased volume growth on an areal basis. A more biologically sound explanation is that individual tree crown expansion continues to occur. Crowns of codominants and dominants expand at the expense of the suppressed trees, thereby inducing mortality in the smaller diameter classes. It follows that the presence or absence of a volume response on an areal basis may not be indicative of a stand's "true" biological response. Because we have been incorrectly quantifying response, it is not surprising that we have been unable to delineate responsive sites.

Redefining Response

In our most recent efforts, we attempted to explain how fertilization affects stand structure (diameter distribution and mortality) and height growth. These efforts were not motivated solely to examine "true" biological response but were undertaken with the realization that changes in stand structure may be a very significant component in the economic evaluation of fertilizer response.

Our latest model quantifies response in terms of 5-year changes in the three Wiebull parameters used to describe the diameter distribution, mortality and dominant height following fertilization as a function of the initial density (stems/ha), age, site index, and treatment (N rate of N+P). The Wiebull distribution and mortality function are used to define stand tables for the stand at the time of treatment and for 5 years later, with and without fertilization (fig. 2). A diameter-height relationship (adjusted for fertilization effects) can then be used to develop estimates of volume response for a particular set of stand conditions (fig. 3).

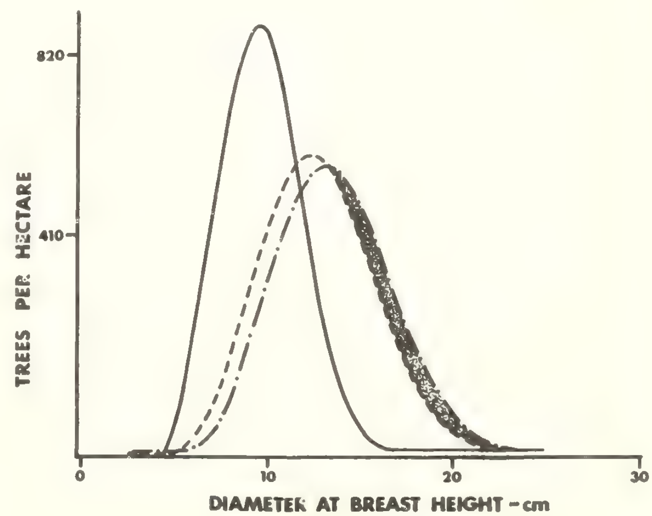

Figure 2.--Hypothetical diameter distributions for a stand prior to a treatment (———) and 5 years later with (—— · —— · ——) and without (— — — —) fertilization.

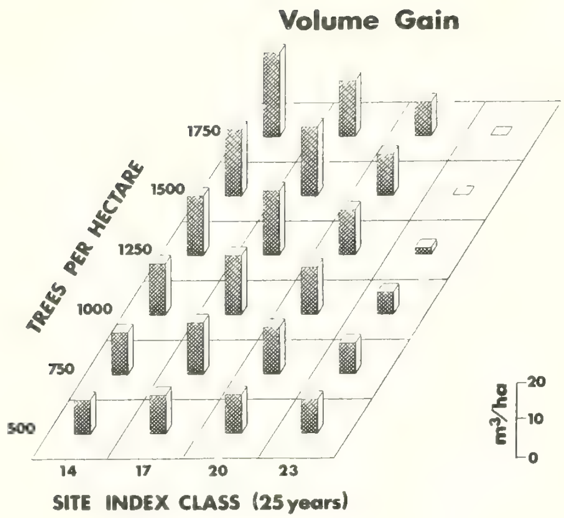

Figure 3.--Five-year volume response following fertilization with 112 kg N and 56 kg P per hectare for non-thinned loblolly pine stands.

More importantly, this same information can be used to merchandise the response and develop an estimate of the dollar value of that response. Unlike past models, the current model gives individual cooperators the flexibility to estimate value responses based on their product mix and price structure. This is an important flexibility because a prescription system based solely on volume gain may not be the same as one developed based on value gain.

Our current model also provides a test for Miller's (1981) hypothesis that fertilizer response may be explained by the analogy of an acceleration in stand development through time. Changes in the Wiebull parameters, mortality, and dominant height over 5 years following fertilization can be compared with changes in these stand parameters over the same 5-year period without fertilization. The difference between changes in these stand parameters can then be related by linear extrapolation to apparent changes in age (fig. 4). Although there is a substantial amount of variability surrounding each of these curves, it is apparent that fertilization has influenced these stand parameters in a similar manner with respect to time.

This hypothesis may only be applicable when fertilization provides for a short-term enhancement in growth and not a long-term improvement in site quality (Miller 1981). A single application of a relatively low rate of nitrogen (< 200 kg N/ha) should fulfill this growth enhancement requirement. The long-term responses to phosphorus on deficient sites of the lower Coastal Plain of the southeastern United States, however, where permanent site improvements are possible should be treated differently.

Interactions with Other Silvicultural Activities

Fertilization, or in the broader sense nutritional management of forest stands, is only one of many silvicultural options available to the forest manager to enhance growth. Because fertilization is only a part of any silvicultural system, an understanding of its interactions with other silvicultural practices such as tree improvement, site preparation, thinning, competition control, and burning is essential.

The cooperative has three regionwide trial series examining the interaction between nitrogen fertilization and thinning. Four-year results from the first series indicated that thinned stands generally are more responsive (in terms of volume and value) to fertilization than non-thinned stands (Ballard et al. 1981). Fertilization also reduced the time required for a stand to regain maximum volume production following thinning. The cooperative's two most recent trial series are examining the relationship between thinning and the timing of fertilization, and the relationship between nitrogen rate and thinning intensity. Data from these trials will provide the basis for much of our future effort.

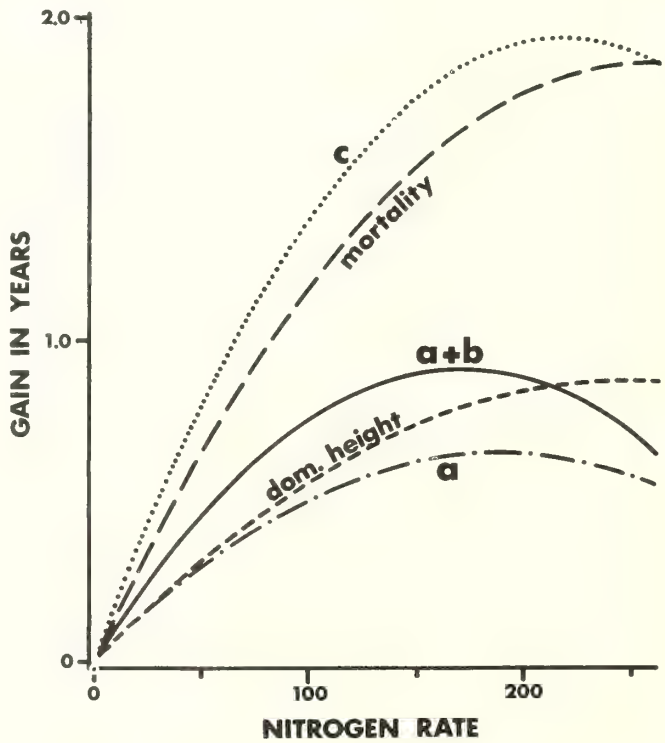

Figure 4.--Five-year response of stand attributes following nitrogen fertilization; a, a + b and c are Wiebull parameters for the diameter distribution.

The cooperative has also established a trial series examining the interactions of site preparation, weed control, and fertilization in newly established plantations. Two-year results from 8 of the 17 installations of this series indicated that weed control and fertilization individually increased growth. Response to fertilization was better, however, when competing vegetation was controlled.

Information from these trials will enable us to place fertilization in the proper perspective as a silvicultural tool.

FUTURE DIRECTION

We are now beginning to re-examine the various traditional measures of nitrogen status (soil and foliar tests) in conjunction with our new concept of stand development response. To augment this array, a number of mineralization indices have been examined (Lea and Ballard 1982); and we plan to continue to expand our efforts in this direction. Because productivity of many loblolly pine sites is limited by moisture and/or phosphorus, our examination of response and nitrogen status will necessarily include an examination of the interactions of response and nitrogen status with these other factors.

The importance of phosphorus nutrition and nitrogen response has long been recognized (Ballard 1980), as has the relationship of nitrogen and moisture (Brix 1981). It has not been until just recently, however, that attempts have been made to account for differences in fertilizer response in relation to available moisture-using soil properties such as texture, moisture content at some specified tension, or drainage class (Fisher and Garbett 1980, Kushla and Fisher 1980). Moisture availability is not only a function of soil properties and topographic position but also reflects the amount and distribution of rainfall and the evapotranspiration potential of a particular site and stand. Integrating all of these factors into a moisture-deficit index and relating this index to nitrogen status and nitrogen response may improve our understanding of the factors influencing nitrogen response. The cooperative has just initiated a new regionwide trial series to address these concerns.

The cooperative has broadened its efforts to include not only fertilization research, but also other aspects of soil and nutritional management as they relate to loblolly pine productivity. These efforts include coordination with other researchers at North Carolina State University in the development and testing of biological nitrogen fixation systems for forestry use. This research has recently expanded to include two new cooperative field trials series to screen effective clover-Rhizobium systems and to test their efficacy for enhancing pine growth.

The cooperative is also actively involved in a project to examine the impact of forest management practices on long-term site productivity. Unlike many of the cooperative's growth impact trials, this project is focusing on how soil, climate, and vegetative regrowth processes are affected by selected harvesting, site preparation, and cultural practices. With this basic knowledge, we can understand how changes in these properties and processes will influence site productivity. The project has gained considerable momentum with the establishment of three field installations and the development of an interdisciplinary research effort focused on process research at these three sites.

All of these efforts, in both basic and applied research, are essential if the cooperative is to continue to provide timely and effective answers to questions concerning the soil and nutritional management of loblolly pine sites.

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THE INTERMOUNTAIN TREE NUTRITION COOPERATIVE

James A. Moore

ABSTRACT: The structure, objectives and activities of the Intermountain Forest Tree Nutrition Cooperative are briefly summarized in this paper. Accomplishments to date and future plans are also discussed.

THE COOPERATIVE

The Intermountain Tree Nutrition Cooperative was initiated in January 1981. The cooperative is conducting forest fertilization research in Oregon and Washington east of the Cascades, in Montana west of the Continental Divide, and in Idaho. The overall objectives of the Cooperative are: (1) to provide nitrogen fertilizer response information for selected species in designated physiographic areas; (2) to estimate response differences for various site and stand conditions encountered within each physiographic area; (3) to develop predictive equations for fertilization response based on site and stand attributes; and (4) to distribute study results to cooperators on a yearly basis and exchange information with other organizations conducting similar fertilization trials. The physiographic areas are shown in figure 1.

The cooperative is presently composed of 13 industrial, federal, and State organizations. These are: Boise Cascade Corporation; Champion Timberlands; Cominco-American; Inland Empire Paper Co.; Longview Fiber Co.; Potlatch Corporation; Union Chemicals Division of Union Oil Co.; Bureau of Indian Affairs Flathead Reservation (Montana); Bureau of Land Management; Intermountain Forest and Range Experiment Station, U.S. Forest Service; Idaho Department of Lands; Washington Department of Natural Resources; and the University of Idaho.

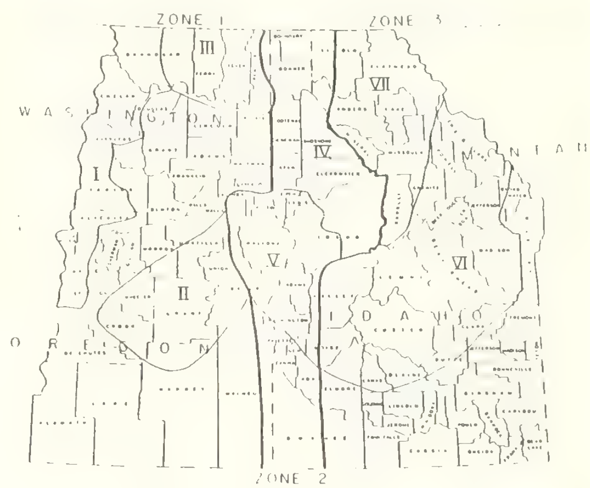

Figure 1.--The seven physiographic regions of the Intermountain Tree Nutrition Cooperative.

The administrative structure of the cooperative includes two committees and the personnel responsible for the project's activities. The research council is composed of one member from each cooperator and this group decides the overall direction for the cooperative. The project steering committee is comprised of fewer people and includes individuals from organizations both within and outside the cooperative. The steering committee provides, as requested, advice and counsel on the technical aspects of the fertilizer trials. Project personnel are the project director, project scientist, and field research associate. Plans are to hire a data analyst in 1983.

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SELECTION OF STUDY SITES

Douglas-fir (Psuedotsuga menziesii (Mirb.) Franco) has been selected as the species of interest for all physiographic areas in the Intermountain Northwest region during the first 2 years of the project; however, many of the test stands contain other tree species, and these will also be included in the analysis. The emphasis will shift to grand fir (white fir) Abies grandis (Dougl. ex D. Don) Lindl., and ponderosa pine Pinus ponderosa Dougl. ex. Laws., for the third and final year of test site selection. In addition to containing a sufficient number of the above species, the following major critera are used in test stand selection: (1) average stand age 35 to 80 years; (2) average stand diameter greater than 12.4 cm (5 in); (3) "well spaced" stands that either occur naturally or result from intermediate treatments; and (4) completion of any treatment at least 5 years prior to the fertilization tests. A total of 130 installations are planned, with 45 to be completed in each of the first 2 years and 40 the third year.

Within each stand a series of six 0.04-ha (0.1-acre) square or rectangular plots are established (fig. 2). A buffer of 7.6 (25 ft) on three sides of the plot and 15.2 (50 ft) on the other will be included for each plot. The larger buffer on one side will provide for any future destructive sampling of trees without disturbing the plots. Two controls and four treatments are randomly assigned to the plots. The treatments consist of: (1) one application of 224 kg/ha (200 lb/acre) actual nitrogen; (2) one application of 448 kg/ha (400 lb/acre) actual nitrogen, (3) two applications of 224 kg/ha nitrogen, and (4) two applications of 448 kg/ha nitrogen. At present we anticipate the second fertilizer treatments will be in the form of urea applied in the fall.

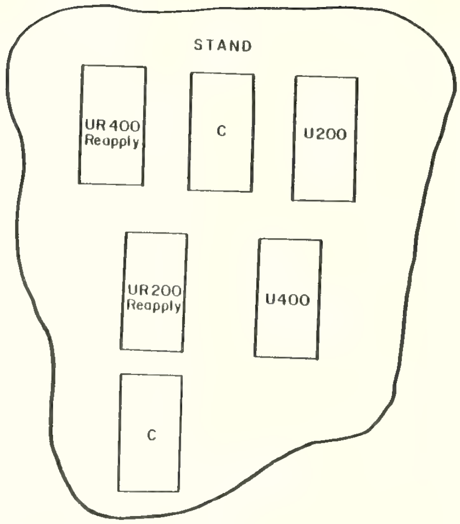

Figure 2.--Plot design and layout and applied treatments for a hypothetical installation (stand). Eight stands will be sampled from each major series of each province. Plot size may vary with the distribution of tree species. C = control; U200 = 224 kg/ha urea-N; U400 = 448 kg/ha urea-N; UR200 = reapply 224 kg/ha. urea; UR400 = reapply 448 kg/ha.

Data to be collected at each site will include the following:

1. Habitat type (or similar floristic evaluation) and abundance ratings for each species in both overstory and understory.

2. Elevation, aspect, slope, topographic position, and other relevant site data.

3. A soil profile description and collection of soil samples from each soil horizon in each stand during the second and third years.

4. A collection of soil samples from the upper 25 cm of each plot the first year before fertilization.

5. Species, crown class, defect, and diameter at breast height (d.b.h.) at the time of treatment application for each tree greater than 5 cm (2 in) d.b.h. on each plot.

6. Total height, crown ratio, and radial growth for each of the past 10 years for all plot trees. Radial growth will be measured the fourth year after treatment.

7. Breast-height ages of selected trees of the study species on each plot.

8. Diameter growth at 2-year intervals following treatment for each plot tree.

9. Total height for all plot trees at 4-year intervals following treatment.

10. Height growth for the past 5 years for all trees less than 10 cm (4 in) (there should be few trees this small in the managed stands to be sampled).

11. Height, divided into three classes, and percent cover for shrub species occurring on the plots.

12. An estimate of percent cover of forbs and grasses on each plot.

ANALYSIS

Growth response for a particular plot will be determined by comparing observed growth after treatment to growth previous to treatment. For each tree sampled, an expected growth will be obtained by projecting previous growth rates. Growth response will then be calculated by subtracting expected growth from observed growth after treatment. In this way the cooperative hopes to correct for microsite differences among the various trees. A simple average of all trees of interest in the plot will serve as the measure of growth response to fertilization. In addition, averages for particular subsets (i.e., potential

crop trees) may also be calculated and analyzed. Factors such as soil characteristics, tree density, and site productivity will be treated as covariates in the analysis.

LABORATORY ANALYSIS

Laboratory analysis to be conducted by project personnel will include soil textural classification, negative hydrogen ion concentration (pH), moisture-holding properties, and organic matter determinations. Chemical analysis involving soil extractions and foliage samples for total available nitrogen will be conducted as part of graduate student research projects. The above soil and foliage physical and chemical properties have been shown to be useful in explaining anomalies in response to nitrogen before treatment could also be included as a variable in a predictive model of fertilization response.

ACCOMPLISHMENTS AND FUTURE PLANS

Forty-five test sites were selected, established, and treated during 1981, and an additional 45 were selected in 1982. Approximately 40 more sites will be established in 1983. The cooperative will begin collecting foliar samples in fall 1982 from the 45 1981 installations. These samples will be used for a new foliar analysis technique that potentially allows the screening of those test stands not likely to respond to treatment only 1 year after application. Professor G. F. Weetman, faculty of Forestry, University of British Columbia, developed the technique working in interior British Columbia. The Intermountain Tree Nutrition Cooperative will also attempt to develop mineralizable soil nitrogen as a useable index of fertilizer response and growth and yield in the Intermountain Northwest region.

FOREST FERTILIZATION RESEARCH IN CALIFORNIA

Robert F. Powers

ABSTRACT: Despite California's importance as a timber growing state, forest fertilization is practiced rarely. Mainly, this is because of the uncertainty managers face in predicting fertilization response and in developing prescriptions for California's varied site conditions. Cooperative fertilization research, begun in 1975, is yielding insight in detecting N deficiency, detailing the characteristics of deficient stands, estimating potential gains from fertilization, and evaluating the fate of N fertilizer.

N deficiencies can be pinpointed by chemical analysis of soil and foliage. Deficiencies are common in all timber types where topsoil has been displaced and in the true fir type where cold soil temperatures inhibit organic matter decomposition and N release. Growth increases from fertilization at 224 to 448 kg N ha^{-1} can be substantial, averaging 36 percent for the 20 oldest study sites and ranging from means of 16 percent for mixed-conifer sites to 81 percent for true fir. Fall fertilization with urea stimulates nitrification and leads to leaching losses of NO_3^- the following spring. Leachate concentrations of NO_3^- are greatest on immature granitic soils but rarely exceed 2 mg N L^{-1} and approach background levels by the second year.

INTRODUCTION

California is a major United States timber producer, second only to Alaska in total forest area. Of its 16 million forested ha, 6.6 million are classified as commercial timberland, capable of growing at least 1.4 m^3 ha^{-1} of wood annually (Bolsinger 1980). But despite California's national prominence, forest fertilization rarely is practiced. Of 81 312 ha treated silviculturally in 1977-1978, only 0.2 percent were fertilized (Bolsinger 1980). Why has a procedure that is common for much of the world not been accepted in California? Reasons trace to several factors.

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FACTORS AFFECTING FERTILIZATION POLICY

Forest Structure and Stocking

Biologically speaking, nitrogen fertilizers are generally most effective near canopy closure (when stands approach full site occupancy and

uptake and immobilization rates are high); following a thinning (when crowns can expand); and near the end of a rotation (where N mineralization rates may drop, inducing a nutrient deficiency (Miller 1981)). Only a low proportion of California's stands meet these conditions.

Summer drought, aggressive weed species and poor management practices place California near the forefront in the United States for nonstocked and understocked commercial forest land. Selective logging has left many stands poorly stocked and low in vigor and quality. Poles, the most biologically responsive size class, account for only 5 percent of stocked forest land. Of that remaining, nearly 90 percent is stocked with sawtimber (U.S. Department of Agriculture, Forest Service 1973). Much sawtimber is old growth, and little is under stocking control. Stocking irregularities hold California stands to half their potential yields (Bolsinger 1980) and draw the attention of most foresters. Yet, gains in regeneration and stocking control practices are improving the structure and size class distribution of California forests, creating a more attractive base for future fertilization.

Site Quality

Fertilizers boost site quality where nutrients are deficient, but California's relatively high site quality may bias many managers against fertilization. California's mean site potential is estimated at 6.8 m^3 ha^{-1} y^{-1}, compared with 5.2 m^3 ha^{-1} y^{-1} for the nation as a whole (Bolsinger 1980). California ranks third nationally in area with yield potentials exceeding 8.4 m^3 ha^{-1} y^{-1} (U.S. Department of Agriculture, Forest Service 1973). Yet, 4.1 million ha are capable of growth rates of only 3.5 to 8.4 m^3 ha^{-1} annually, and the State's 9.9 million ha of noncommercial forest is second in size only to Alaska's. On many sites, nutrition may be an overlooked, but correctable, limiting factor.

Complexity

California is known for its floristic, climatic, and geologic diversity that complicates site assessment. More than 80 tree species are native to the State and 21 are endemic (Griffin and Critchfield 1972). Of these, about a dozen conifers are commercially important and comprise five major timber types (fig. 1). Topographic features shape climate and create steep gradients in moisture and temperature that increase site complexity. The north-south alignment of California's four major mountain ranges (fig. 1) causes orographic precipitation from moist Pacific air on western slopes, and produces dry, rain shadows to the east. Accordingly, annual precipitation may vary by nearly 200 cm in the span of a few kilometers. Altitudinal limits of the commercial forest extend from nearly sea level stands of redwood (Sequoia sempervirens [D. Don] Endl.) to 2 100-m Sierra Nevada forests of red fir (Abies magnifica A. Murr.). Within

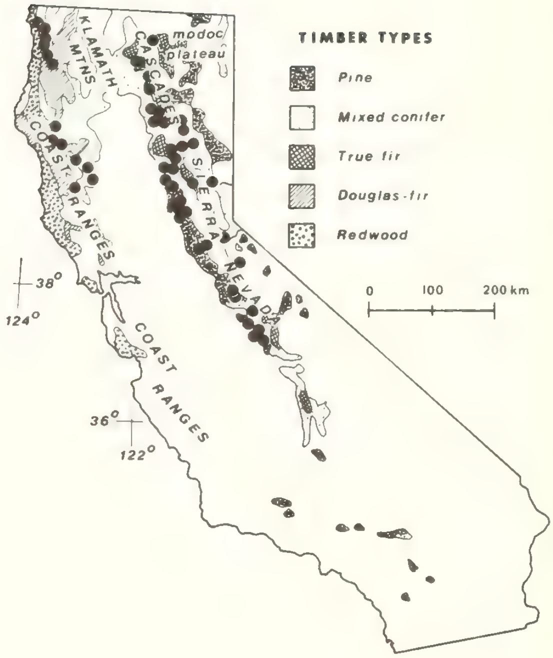

Figure 1--Distribution of commercial timber types in California and the geomorphic provinces in which they grow. Dark circles indicate location of fertilization installations.

this zone, mean July temperatures vary from 15° to 24°C (Alexander 1981). Winter minima range from slightly below freezing during brief periods along the coast to as low as -32°C in the Sierra Nevada (Fowells 1965).

Although nearly 200 upland soil series have been identified in California, Colwell (1979) estimated that another one-third may await classification. A major factor contributing to California's soil diversity is its varied geology (Norris and Webb 1976). For example, the Coast Ranges, containing all of the redwood and much of the Douglas-fir (Pseudotsuga menziessi [Mirb.] Franco) forests, consist of two separate complexes separated by the San Andreas Fault. East of the fault are Jurassic-Cretaceous sediments (sandstones on the west, schists on the east). West of the fault lay Cretaceous granitic intrusives and older sedimentaries. Elevations are relatively low, with most peaks reaching 900 to 1 050 m.

The Klamath Mountains are higher, more complex, and produce forests of mixed conifers and Douglas-fir. General elevations vary from 1 500 to 2 100 m. Geology includes two belts of synclinal and plutonic rocks dating from the Ordovician Period to the Jurassic, underlaying Cretaceous marine sediments. The western belt is comprised of Paleozoic and Triassic schists, volcanics, and limestones, intruded by ultramafics and granitics. The eastern belt consists mainly of Paleozoic sediments and volanics.

The Cascade Range consists of volcanic mountains supporting stands of pine, mixed conifers and fir, with high peaks and a general elevation of 1 200 m. Rocks are Pliocene andesites, often overlain by Pleistocene flows of basalt. Pliocene to Recent deposits of ash, tuff, and pumice occur extensively. East of the Cascade Range lies the Modoc Plateau, an undulating platform of Miocene to Recent basaltic flows supporting extensive stands of ponderosa pine (Pinus ponderosa Dougl. ex Laws.) at average elevations of 1 200 to 1 500 m.

The Sierra Nevada, a 640-km-long, west-tipped, fault block related to the Klamath Mountains, emerges from beneath the southern lavas of the Cascade Range. There, the Sierras begin as metamorphosed early Mesozoic volcanics and sediments underlain by Jurassic-Cretaceous granitics that are exposed from the mid-Sierra, south. Western slopes vary in elevation from 120 m at the valley floor to more than 4 200 m at the crest, and support extensive forests of ponderosa pine, mixed conifers, white fir (Abies concolor [Gord. & Glend.] Lindl. ex Hildebr.), and red fir. The steep, dry, eastern scarp supports stands of Jeffrey pine (Pinus jeffreyi Grev. & Balf.).

The baffling array of forest and soil combinations emerging from California's climatic and geologic diversity presents a formidable obstacle to those considering forest fertilization over broad areas. That same array, however, provides researchers with a rare opportunity to test nutritional hypotheses over a broad environmental spectrum.

Uncertainty

Fertilizer trials in California trace at least to the mid-1950s (Zinke 1965) and 34 separate studies involving 26 investigators were known to be active in 1975 (Zinke et al. 1975). Few data have been reported and none have been organized to produce a general model predicting fertilizer response. Indeed, the disparity of the early studies probably precludes general, meaningful conclusions.

Of the 34 studies identified in 1975, nearly half were on soils derived from basic igneous rock and many were on ultramafic soils of limited extent. None were on soils of granitic origin, although such soils represent vast areas of the Sierra Nevada and Klamath Mountains. Two-thirds of the studies involved ponderosa or Jeffrey pine, although the pine type comprises but one-fourth of California's commercial forest. Soil or foliar analysis procedures that could extend findings to broader areas were practiced at less than a third of the sites and only one study considered water quality. Faced with rising operating costs and the lack of sound guidelines, California managers have been justified in not embracing forest fertilization.

A SYSTEMATIC APPROACH

In 1975, the USDA Forest Service California Region and Pacific Southwest Forest and Range Experiment Station began a cooperative program of research aimed at developing principles for predicting forest fertilization response in California. The goal was to establish installations on 50 benchmark combinations of timber and soil types by 1980 using a standard, randomized-block experimental design. Even-aged stands in sapling through large pole size classes were chosen for study. Treatments consisted of 0, 224 and 448 kg N ha^{-1} applied as urea after the first fall rains. Fall application was chosen to ensure hydrolysis of urea and minimize volatilization losses during dry springs. Factorial combinations of weeding or thinning also were included, depending on stand condition.

Soils at each site were classified to the series level using standard procedures (Soil Survey Staff 1975) and sites were characterized nutritionally using soil and foliar analyses. Soil N availability was estimated by anaerobic incubation from composited samples taken at 20-cm depth (Powers 1980), and from total Kjeldahl N in current- and previous-year foliage from upper crowns of dominant trees sampled in late summer. On-site soil water extractions were made at several depths on treated and untreated plots after major storms using porous cup soil water samplers and portable vacuum pumps. Samples were analyzed for NH_4^+ and NO_3^-. Heights and diameters were measured in all study plots at the start of treatments and again 5 years later. A few sites have been studied more intensively.

RESULTS

By 1980, 51 installations had been established in all major timber types except redwood (fig. 1). Although research is still in progress, results from the 20 oldest installations offer leads in identifying responding stands and in estimating their growth response to fertilizer N.

Stand Characteristics and Growth Response

Characteristics of 20 study sites with the longest response records are shown in table 1. Growth response was measured as percentage differences in height, basal area or volume increment between fertilized and control plots, using regression and covariance analysis to adjust for differing initial tree sizes. Responses were expressed as percentages to provide a common response variable for all sites. Because growth

Table 1--Characteristics of 20 study sites and their growth response to fertilization at 224 to 448 kg N ha^{-1}

Forest type	Parent material	Stand cond.[1/]	Size class	Soil temp. regime	Min. soil N	Foliar N	Treat. period	Growth var. [2/]	Growth resp. [3/]
					(ppm)	(percent)	(y)		(percent)
Pine	Schist	P_t	Sm. sapling	Mesic	7	0.92	5	H	70
Pine	Greenstone	N	Sapling	Mesic	24	1.00	5	H	3
Pine	Ash	P_t	Sapling	Frigid	15	0.99	5	B	22
Pine	Basalt	P_t	Sapling	Mesic	9	0.98	5	H	20
Pine	Schist	P_t	Sapling	Mesic	4	0.87	5	H	67
Pine	Ash	P	Sm. pole	Frigid	16	1.25	6	V	41
Pine	Andesite	P	Pole	Mesic	30	1.19	5	V	0
Pine	Andesite	P	Pole	Mesic	19	1.19	5	V	8
Pine	Basalt	P	Pole	Mesic	12	1.18	5	B	9
Pine	Basalt	P	Pole	Mesic	12	1.13	5	B	15
Pine	Schist	P_t	Pole	Mesic	11	1.11	5	B	40
Pine	Greenstone	N	Lg. pole	Mesic	12	0.88	5	B	72
Douglas-fir	Schist	P	Sapling	Mesic	19	1.19	5	B	-12
Mixed-conifer	Schist	P	Sm. sapling	Mesic	35	1.42	3	H	-8
Mixed-conifer	Diorite	P	Sapling	Mesic	12	1.29	5	B	24
Mixed-conifer	Ash	N	Pole	Frigid	15	1.11	6	V	31
True fir	Andesite	N_t	Sm. sapling	Frigid	13	0.95	5	H	41
True fir	Ash	N_t	Sm. sapling	Frigid	8	1.15	5	H	78
True fir	Pumice	N	Sm. pole	Frigid	5	1.00	5	V	134
True fir	Andesite	N	Lg. pole	Frigid	14	1.12	5	B	70

1/ Planted (P) or Natural (N) stand. Subscript (t) denotes sizable displacement of topsoil.
2/ Height (H), Basal area (B), or Volume (V) growth variables.
3/ Percentage growth response relative to control.

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responses were similar to both 224 and 448 kg N ha^{-1}, responses were averaged for these two rates.

In general, mixed-conifer stands show the least gain to N fertilization (16 percent) and true fir stands the most (81 percent). Although three installations are inadequate for characterizing a timber type as broad and important as California's mixed-conifer, high average values of mineralizable soil N (21 ppm) and foliar N (1.27 percent) suggest that soil N deficiency may be relatively rare in mixed-conifer forests. In contrast, all true fir study sites responded strongly to fertilization, with 5-year growth gains ranging between 41 and 134 percent. Average values of mineralizable N (10 ppm) and foliar N (1.06 percent) are the lowest of any timber type, supporting the contention that cold soil temperatures characterizing the true fir zone retard N mineralization rates and induce general deficiencies (Powers 1980, 1981b). Classifying all sites by soil temperature regime (Soil Survey Staff 1975) shows that stands with frigid soils average more than twice the growth response to fertilization (60 percent) as stands with mesic soils (24 percent).

Stands with soils of volcanic and metasedimentary origin averaged similar fertilization responses--39 and 32 percent, respectively. Separating volcanics into further categories, however, shows that stands on soils weathered from ash deposits had nearly twice the response as stands on andesitic or basaltic flows. Unfortunately, trends are confounded in that all study sites on ash have frigid soil temperatures, and those on andesite and basalt primarily are mesic.

More than half the study sites reported here are forested with pine, and most of these are plantations. Although plantation growth response averaged only 29 percent overall, both soil parent material and soil surface condition seem related to response. Stands established on sites with little or no topsoil displacement during site preparation showed little fertilization response (only 15 percent). Both mineralizable

Table 2--Five-year effects of fertilization and weeding on height increment and foliar N concentration in 15-year-old ponderosa pine planted on soils developed on schist (poorer site) and basalt (better site)

Treatment	Poorer site[1]			Better site[2]		
	Height growth	Foliar N current	Foliar N 1 year old	Height growth	Foliar N current	Foliar N 1 year old
	(m)	- - - - percent - - - -		(m)	- - - - percent - - - -	
Control	0.60	0.87	0.71	1.44	0.98	0.80
N only[3]	0.66	0.83	0.76	2.08	1.05	0.94
Weeding	1.23	0.92	0.78	2.42	1.14	0.88
N + weeding	2.05	0.98	0.86	3.21	1.26	1.01

1/ Site index 15 m at 50 years.

2/ Site index 30 m at 50 years.

3/ 224 kg N ha^{-1}.

soil N (18 ppm) and foliar N (1.19 percent) were at satisfactory levels for ponderosa pine (Powers 1980, Powers and Jackson 1978). In contrast, soil N averaged only 9 ppm and foliar N only 0.97 percent for sites where topsoil had been scalped into windrows. There, fertilization response averaged 44 percent, suggesting that topsoil displacement markedly decreased soil fertility and potential site productivity. Of the plantations with topsoil displacement, those on soils derived from schist averaged about half the mineralizable N and showed nearly three times the fertilization response as those on volcanics.

Limiting Factors

Drought is common in California and fertilization response is conditioned by available soil moisture. The most aggressive competitors of trees for soil moisture are woody shrubs. On shallow or skeletal soils, shrub competition aggravates stress from climatic drought and may block fertilization response even where N deficiency is severe. For example, 5-year results of N fertilization are shown in table 2 for 15-year-old ponderosa pine plantations on adjacent, but contrasting, sites. Both plantations support dense stands of woody shrubs (Arctostaphylos sp. L.), averaging 32 t ha^{-1} on the poorer site and 42 t ha^{-1} on the better one. Soil on the poorer site is a shallow, gravelly silt-loam derived from schist. On the better site, soil is a deep clay-loam weathered from basalt.

Although shrub biomass was lowest on the poorer site, its competitive effect was greater. Predawn xylem moisture tension measured in dominant trees late in the growing season averaged 1.5 MPa where shrubs were present, compared with 0.9 MPa on plots weeded 5 years before. Unweeded plots did not respond to N fertilization, but height growth was doubled and moisture stress was nearly halved simply by weeding the stand. Combining weeding with fertilization nearly doubled growth again, showing that weeding and fertilization work synergistically on poor sites, with effects evident as early as the first year (Powers and Jackson 1978). Although shrubs had one-third greater biomass on the better site, they were not as competitive because of better soil development. There, predawn xylem moisture tension averaged 1.2 MPa where shrubs were present and was only 11 percent lower on weeded plots. Consequently, moisture stress did not preclude fertilization response and effects were additive, rather than synergistic (table 2).

Although growth responses were proportionally greater on the poorer site, absolute growth was not as great as on the better site and low foliar N concentrations suggest that fertilizer effects will end soon. In contrast, foliar N concentrations remain high in both current and year-old needles on the better site, indicating that fertilizer effects will continue and that better sites are more effective at retaining fertilizer N.

Groundwater Quality

Urea fertilization in the fall at 224 kg N ha^{-1} over a wide range of soil types and stand conditions produces changes in soil solution chemistry that are greatest the first spring following treatment. Although soil solution NH_4^+ concentrations rarely reach 4 mg N L^{-1}, NO_3^- concentrations can be much higher (table 3). The spring peak for NO_3^- reflects high nitrifier activity when moisture, temperature and NH_4^+ substrate are not limiting. Concentrations decline as soils dry during the summer, but fall rains bring a secondary NO_3^- peak stemming both from renewed nitrifier activity and leaching of

Table 3--Maximum concentrations of soil solution NH_4-N and NO_3-N extracted at 0.08 MPa suction at 50-cm depth by soil type in plots unfertilized and fertilized with 224 kg N ha^{-1}

Parent material	Profile development1/	Nitrogen concentration when treatment was--2/			
		control	fertilized	control	fertilized
		- - (mg NH_4-N L^{-1}) - -		- - (mg NO_3-N L^{-1}) - -	
Acid igneous	Immature	0.92	4.39	1.09	17.15
	Mature	0.50	1.23	0.48	1.06
Basic igneous	Immature	0.79	3.68	1.70	12.97
	Mature	1.10	0.76	3.18	3.48
Meta-sedimentary	Immature	0.96	0.60	0.78	3.90
	Mature	0.65	1.54	0.21	8.34

1/ Immature soils lack conspicuous B horizons.

2/ Based on 40 installations, first 2 years after treatment.

NO_3^- accumulated over the summer. Except for very brief periods, NO_3^- concentrations rarely reach standard public health limits of 10 mg N L^{-1}. Leaching losses seem minor and are associated mainly with coarse-textured, immature soils.

Diagnosing Deficiency and Predicting Response

Used properly, both foliar and soil chemical analyses provide effective indices of N deficiency. Foliar analysis has the advantage of directly measuring the nutrient status of the tree for the full spectrum of mineral nutrients. Its disadvantages are known well (van den Driessche 1981), and include sensitivity to crown position, needle age, and season of sampling. For example, analysis of N concentrations in current-year foliage from the poor and better sites described in table 2 could lead to conflicting conclusions. Samples collected in May from current-year needles after bud burst yield extremely high N concentrations with no appreciable differences between sites (fig. 2), implying that both sites are well-supplied with N. Sampling the same sites in August, after growth had ended, also shows little difference between sites, but now suggests that both sites are severely deficient in N.

Both sampling periods are inappropriate. Spring sampling is misleading because N concentrations invariably are high in immature, expanding needles on even the poorest sites, and bear little relationship to the availability of soil N. Sampling after growth has been completed--the conventional practice--is an improvement, but still fails to discriminate between sites with important differences in fertility. Assuming a critical N level of 0.95 percent, trees on the poorer site were under severe N stress since the beginning of July, but those on the better site were adequately supplied into August when growth was essentially complete. Sampling after growth has been completed will not detect midseason nutrient stress, nor suggest the resulting loss in potential growth. The sampling time that best distinguishes severely deficient sites from those marginally deficient is near the culmination of seasonal growth when trees are placing strong demand on their internal reserves and on those of the soil. In fig. 2, this corresponds to early summer when most needles have expanded fully and growth is nearing completion.

Sampling year-old needles as well as current needles is proposed to minimize seasonal variation and improve diagnostic accuracy.

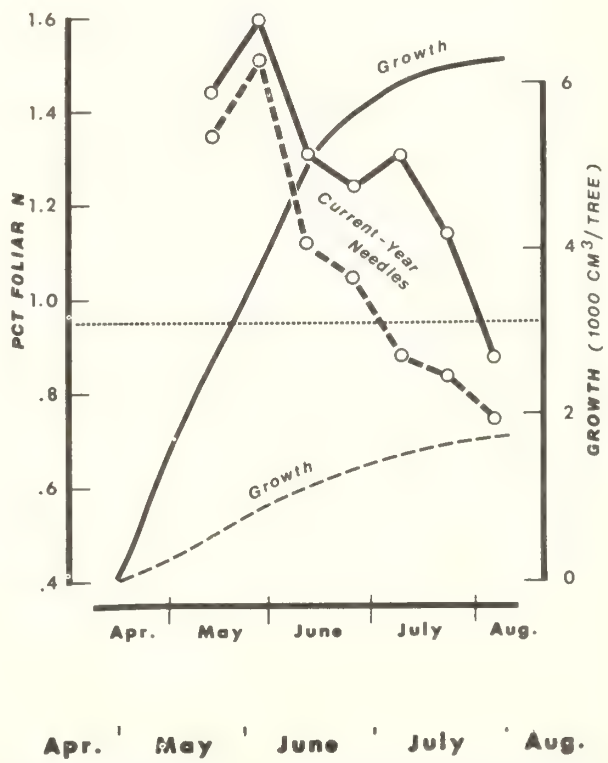

Figure 2--Changes in tree volume and N concentration in current-year needles for ponderosa pine growing on a poor site (broken curves) and a better site (solid curves). Horizontal line marks a critical level of 0.95 percent N. Basis: 9 trees on the poor site, 10 on the better.

Analysis of year-old foliage has distinct advantages. Because such foliage receives little shading, it retains its potential for normal rates of photosynthesis (Helms et al. 1974) and is the main source of photosynthate for current growth processes. Also, needle weights vary little beyond the first year and N concentration will not be affected by growth dilution artifacts found in current-year needles. Concentration levels and changes provide a true index of the stability of N supply. Constant, high concentrations throughout the growing season indicate that N is not limiting growth. Falling concentrations mean that demand exceeds supply because N is translocated from year-old needles to current needles faster than it is translocated into them. If concentrations dip below critical level, N stress occurs and growth will be lost. The earlier and more severe the dip, the greater the period and degree of stress.

Analysis of older foliage from the same sites described in fig. 2 shows that N supply on the poorer site fell short of demand. On that site, concentrations in year-old needles were always less than the critical level of 0.95 percent N, and growth was always poor (fig. 3). By late June, stress levels were reached in current needles and concentrations in year-old needles plunged sharply. In contrast, N concentrations remained above the critical level until July in year-old needles on the better site and growth rates were high until then.

Results suggest that the effectiveness of foliar analysis can be improved markedly by analyzing both current and year-old foliage collected just before the culmination of annual growth. In the example given, sampling in early July would reveal high N concentrations in current needles and a slight deficiency in older. Although some fertilization response could be expected, it probably would not be great (5-year response was 33 percent, table 2). Sampling the poorer site then would show critically low N concentrations in both current and older needles, indicating a severe N deficiency and a potentially strong response to fertilization (67 percent, table 2).

Properly interpreting foliar analyses demands an understanding of critical nutrient concentrations marking the boundaries between nutritional sufficiency and severe stress. Critical levels of N and P are proposed for ponderosa and Jeffrey pine, Douglas-fir and white and red fir (table 4) and are based on controlled environment and field experimentation (Powers 1981a). Critical levels for K, Ca and Mg also are proposed, based on conservative lower limits of Ingestad's (1974) optimal proportions applied to the critical levels proposed for N. Also shown are means and ranges of nutrient concentrations found in current, upper crown foliage from sampling unfertilized stands throughout California. Findings are comparable with Zinke and Stangenberger's (1981) independent survey of ponderosa pine and Douglas-fir.

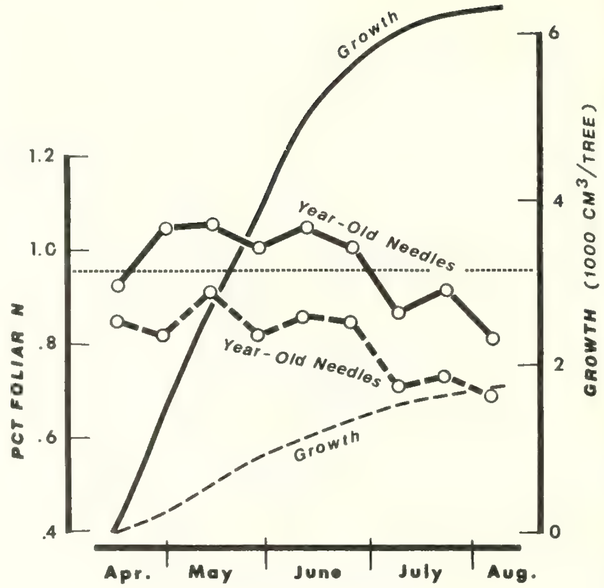

Figure 3--Changes in tree volume and N concentration in year-old needles for ponderosa pine growing on a poor site (broken curves) and a better site (solid curves). Horizontal line marks a critical level of 0.95 percent N. Basis: 9 trees on the poor site, 10 on the better.

Relative to other species, ponderosa and Jeffrey pines have low foliar nutrient critical levels. This, coupled with comparatively high mean values in field samples, suggests that fertilization opportunities may be more limited in pine than in other species. K nutrition, however, warrants further study. Judging from the mean values in table 4 and elsewhere (Zinke and Stangenberger 1981), a high proportion of California's Douglas-fir stands may be N deficient, but other nutrients generally seem adequate. Foliar P concentration in red and white fir averages less than critical level and points to the need for factorial trials of N and P fertilizers in the true fir type.

Not enough fertilization trial data have been gathered yet to rigorously test foliar N as a predictor of treatment response. Grouping response data from table 1 into foliar N classes, however, shows that pine stands testing less than critical level averaged 70 percent growth response to fertilization. Stands testing between critical level and 1.15 percent N averaged 20 percent response, and those testing higher averaged 14 percent. Foliar N was at or below critical level in all true fir stands tested, and all responded strongly to treatment. Of the three mixed-conifer sites, only those testing less than 1.30 percent foliar N responded

Table 4--Critical levels and characteristics of macronutrient concentrations in current-year needles of commercial conifers in California

Species	Characteristic	Foliar nutrient concentration[1]				
		N	P	K	Ca	Mg
		percent				
Ponderosa and Jeffrey pine n = 170	Critical Level	0.95	0.08	0.48	0.05	0.05
	Mean	1.15	0.13	0.52	0.15	0.11
	Range	0.58-2.11	0.03-0.38	0.17-1.12	0.01-0.54	0.04-0.27
Douglas-fir n = 16	Critical Level	1.20	0.15	0.60	0.12	0.06
	Mean	1.05	0.18	0.72	0.19	0.09
	Range	0.58-1.89	0.05-0.30	0.54-1.03	0.02-0.33	0.05-0.21
White and red fir n = 54	Critical Level	1.15	0.15	0.58	0.12	0.06
	Mean	1.16	0.13	0.88	0.40	0.08
	Range	0.66-2.12	0.03-0.27	0.56-1.22	0.09-0.91	0.04-0.15

1/ Concentrations measured in upper crown foliage late in the growing season. Critical levels for N and P based on experimentation (Powers 1981a); K, Ca, and Mg based on lower limits for optimal proportions with N = 100 (Ingestad 1974).

well to fertilization.[1]

Soil analysis for mineralizable N has been found effective in screening stands for N deficiency (Powers 1980, Shumway and Atkinson 1978). Advantages of the test are that it provides an index of release rate of organic soil N affected little by season of sampling and it is simple to use. At present, it is the most effective, practical test of soil N availability. Its main disadvantage is that results are based on standard laboratory conditions and do not mimic the natural environment. Particularly troublesome are the effects of differing field temperatures (Powers 1980).

Research is underway to learn how field soil temperatures affect natural mineralization of organic soil N and how the mineralizable N index can be adjusted for California's broad range of forest soil temperatures. In the interim, the standard test can be strengthened by stratifying calibration data in table 1 into soil temperature regimes (fig. 4). Fertilization response can then be expressed as a function of mineralizable soil N as follows:

for mesic soils,

$$y + 13 = 286.8\ e^{-.2369x} + .0038x^2$$

$$R^2 = 0.49;$$

and for frigid soils

$$y + 13 = 322.2\ e^{-.1809x} + .0038x^2$$

$$R^2 = 0.75$$

where:

y = 5-year growth response to fertilization as a percentage of the growth of unfertilized stands,

x = mineralizable soil N in ppm, and

R^2 = coefficient of determination.

These functions are simply a first step in effectively predicting stand response to N fertilization and will improve as new data are gathered from installations reaching their fifth growing season from treatment.

SUMMARY

The USDA Forest Service cooperative program described here is a limited but effective systematic approach for discovering principles governing soil N availability in California forests and developing ways of predicting fertilization response. Although research is far from com-

1/Foliar N concentrations for mixed-conifer stands are average values for all species in dominant canopy positions. Generally, this includes ponderosa pine, sugar pine (<u>Pinus lambertiana</u> Dougl.), and white fir.

plete, interim results offer leads in locating N-deficient stands and estimating approximate fertilization response.

Stands most likely to be N deficient are those on soils derived from schist with noticeable topsoil loss. Stands on soils with frigid temperature regimes show responses to fertilization that are greater, on the average, than stands on mesic soils. Other site factors being equal, true fir are more likely to respond to fertilization than pine. Not only is N availability depressed by cold temperatures in the true fir zone, but foliar N requirements are higher in fir than in pine.

Foliar analysis promises to be an effective means for identifying stands with N and other nutrient deficiencies, provided that samples are collected late in the growing season. Trends suggest that foliar analysis may also afford a way of predicting the magnitude of fertilization response if both current and year-old needles are analyzed separately. Soil analysis using the mineralizable N procedure offers California's first means for predicting the degree of fertilization response; but the test must be honed further to account for California's broad array of soil temperatures and to predict yield in absolute, rather than relative, amounts.

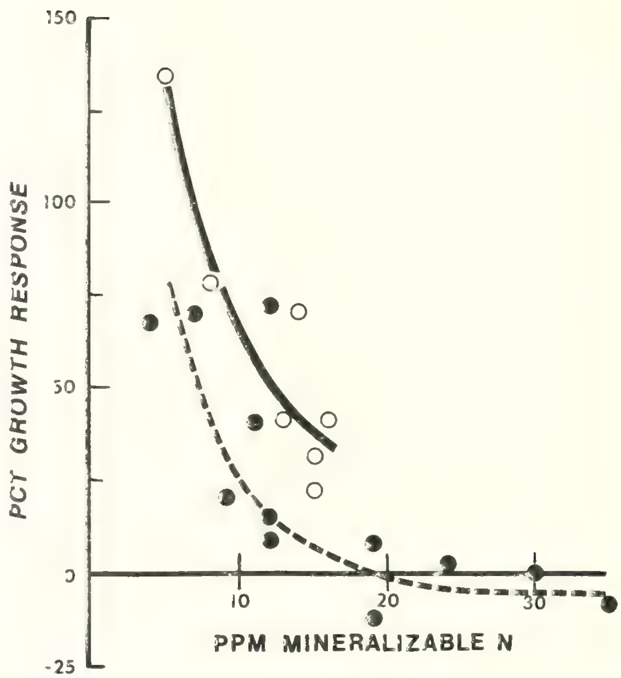

Figure 4--Five-year relative growth response of California stands to urea fertilization at 224 to 448 kg N ha^{-1}. Solid curve and open circles are for stands on frigid soils. Broken curve and solid circles are for stands on mesic soils.

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A COMPARISON OF GROWTH PROMOTION BY CONTROLLED RELEASE UREAS AND CONVENTIONAL NITROGEN FERTILIZERS USING TWO MENSURATIONAL METHODS

Peter O. Salonius and M.K. Mahendrappa

ABSTRACT: Various nitrogen carriers were applied to black spruce. After ten growing seasons posttreatment volume growth increases were calculated using conventional diameter breast height measurements and height-diameter curves. Ratios of posttreatment to pretreatment radial growth were also determined such that the growth of each plot before and after fertilization could be compared.

INTRODUCTION

Coniferous forest soils in the north temperate zone are often deficient in plant-available nitrogen (Lowry 1975). Crop recoveries of applied nitrogen fertilizers in forest fertilization trials have been low (Morrison and Foster 1977) compared with those reported in agriculture (Beaton et al. 1967). Studies in Scandinavia have shown that in northern European forests (Bengtson 1973) ammonium nitrate is superior to conventional urea application. Nitrogen uptake by conifers has been shown to continue throughout the growing season (Salonius 1977); however the availability of soluble formulations is highest in the short period immediately after application. There has been considerable interest in recent years in controlled release formulations of nitrogen for forest fertilization to circumvent various avenues of loss that decrease fertilizer efficiency (Mahendrappa and Salonius 1974, Salonius 1978). Various controlled release formulations have been developed, such as urea formaldehyde and resin-, sulfur-, and plastic-coated materials. In this study, the efficacy of plastic-coated urea (Salonius and Adams 1972) and sulfur-coated urea was compared with that of soluble urea, calcium nitrate, and ammonium nitrate.

The predictability of growth responses of forest crops to fertilizer treatments in Canada (Weetman et al. 1979) and elsewhere (Ballard 1979, Shoulders and Wittwer 1979) is low, even though numerous experiments have been conducted with various species on various site types. This low predictability may be partly because methods for measuring response in forestry have been adapted from agricultural research where stocking, population structure, site characteristics, and microclimate on control and treated plots are more uniform (Salonius et al. 1982). Conventional methods of measuring fertilizer response, exemplified by a large cooperative Canadian study (Weetman et al. 1976, 1978, 1979), generally accept differences between posttreatment growth on control and treated plots as indicative of the effects of fertilizer application. These studies attempt to circumvent bias in the results, caused by variation in initial volume between treatments, using analysis of covariance. The difficulties encountered

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in forestry of choosing representative controls based on stand and site characteristics (Salonius 1981), have led some workers (Hall et al. 1980, Mahendrappa and Salonius 1982, Salonius et al. 1982, Wells et al. 1976) to investigate alternative methods of measuring fertilizer response. In this study, we compared the conventional approach (posttreatment growth on control and treated plots is measured) and an alternative method (each tree or treatment is its own control) (Salonius et al. 1982).

METHODS AND MATERIALS

The semimature black spruce stand (*Picea mariana* (Mill.) B.S.P.) in which this work was carried out is located near Juniper in west-central New Brunswick, Canada. The stand was approximately 55 years old at the outset of experimental work. The stand grows on a moderately well-drained, mini-humoferric podzol (Canada Soil Survey Committee 1978) where the cover on the forest floor is mainly feather mosses (*Pleurozium* spp., *Hypnum* spp., and *Hylocomium* spp.) with scattered *Sphagnum* spp. in wet depressions.

This forest type has been exposed to varying intensities of spruce budworm (*Choristoneura fumiferana* (Clem.)) infestation for at least the last 20 years.

The experiment consisted of 33 circular 0.04-ha plots in which the inner 0.02-ha circle was reserved for measurement and the outer 0.02-ha circle was a buffer zone such that the roots of all measured trees in fertilized plots were within the treatment area. Plots were established at least 20 m apart to avoid contamination of controls by volatilized ammonia and possible cross-feeding by roots. Plot treatments consisted of 112(1) and 280 kg N/ha(2) as calcium nitrate, ammonium nitrate, plastic-coated urea (Salonius and Adams 1972), sulfur-coated urea (nominal dissolution rate 15.4 percent in 7 days; 22 percent sulfur, 3 percent wax, and 0.25 percent coal tar by weight, from Tennessee Valley Authority), conventional urea, and controls. Three replicates of each treatment were assigned randomly to the plots and the fertilizer was applied in late June 1971.

All living trees over 5-cm diameter at breast height in the inner 0.02-ha circle were numbered, and a spot was painted at or near breast height. Breast height diameter was measured at the painted spot before fertilizer application and again 10 growing seasons after treatment. Height-diameter relationships were recorded on untreated plots at the outset and conclusion of the experiment so that original and final volumes could be derived using Honer's (1967) volume tables adjusted to local conditions. Mortality in terms of original volume and volume growth in the posttreatment period were calculated by the conventional method of determining growth response.

For the alternative method of measuring response, where each tree or treatment is its own control, two increment cores were taken at breast height from each tree, one on the south side and one on the north side. Each increment core included at least 20 rings. On each core, ring widths were measured with an Addo-X machine for the 10 years before and the 10 years after fertilizer treatment.

RESULTS AND DISCUSSION

Mortality as a percentage of original volume (numbers below the bars) and in terms of actual volume is reported in figure 1, as is increase in volume on trees that were still alive 10 years after fertilization. If net merchantable volume had been added to mortality volume (fig. 1), the presentation would have represented gross merchantable volume. For comparison the increase in volume on surviving trees is given as a percentage of the initial volume on those same trees before fertilizer treatment (numbers at the top of the histogram bars). This is the conventional mensurational approach for determining fertilizer response where increased growth in the period after treatment is taken to be indicative of fertilizer effect when compared with growth in the untreated condition. It is evident that, even though plots were chosen carefully to be similarly stocked, there are considerable discrepancies between the response pattern suggested by actual increase in volume and that indicated by percentage increase on the original volume base. This difficulty has been discussed at some length in a recent paper (Salonius 1981).

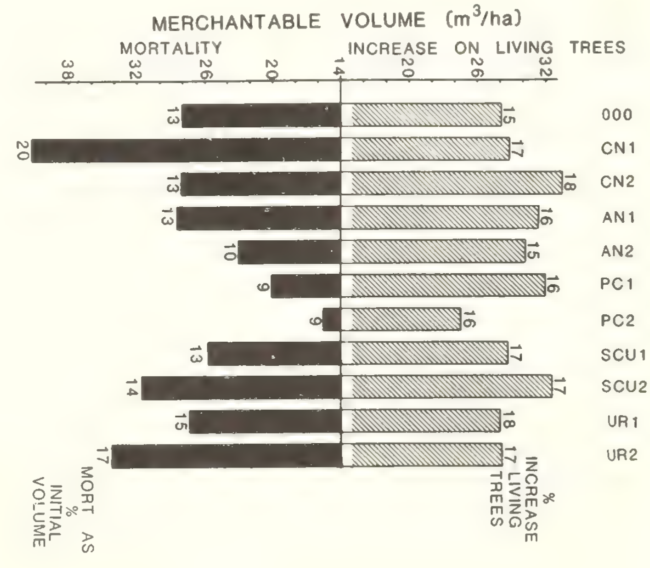

Figure 1.--Merchantable volume growth on survivors and mortality of black spruce in the post-fertilization period.

When simple radial growth, taken from the increment cores, is examined (fig. 2) it becomes apparent that the relationship of tree growth in the various treatments in the 10 years after fertilization is generally similar to the relationship of tree growth in the various treatments in the 10 years before fertilization (Salonius et al. 1982). Mean radial growth of the three urea treatments, however, while less than that of the control in the prefertilization 10 years, is greater than that of the control in the postfertilization 10 years. Differential stocking, different growth rates, and differences in site, microclimate, and population structure within this fairly uniform forest have made it difficult or impossible to assess actual response to fertilizer by conventional posttreatment growth measurements (Wells et al. 1976).

We reasoned that, if prefertilization growth rate was so important in determining postfertilization growth rates that the best predictor of future growth is past growth performance, another approach that recognizes this phenomenon was warranted (Salonius et al. 1982).

Our manner of handling the influence of pretreatment growth rates was to simply sum 10 years of radial growth for all living trees after treatment (R_2) and report that growth as a percentage of summed radial growth for the same trees in the 10 years before treatment (R_1). This ratio method ($R_2:R_1$) in effect makes each tree or treatment its own control because posttreatment growth is compared with pretreatment growth. Calculations using this method show that the trees in the control plots produced 56.4 percent of their pretreatment radial growth in the 10 years after fertilizer was applied to the treated plots. Similar calculations show the largest value to be 63.6 percent (fig. 3) in plots treated with 280 kg N/ha as urea (UR2). Relative response is represented by the differences between the radial growth ratios of the treatments and that of the control.

The comparison of the results from different treatments (fig. 3), which we think is more realistic because it considers pretreatment growth rates, stands in contrast to the same comparisons by the conventional method that uses posttreatment volume growth (fig. 1). With the conventional method, several treatments show no stimulus to growth or even an apparent inhibition.

It would be desirable to express response in terms of volume for this and several other fertilizer experiments in mature and semimature forest stands. In these experiments, we have a fairly good measure of volume growth in the posttreatment period determined by conventional methods. Radial growth ratios ($R_2:R_1$) at breast height and volume growth ratios ($V_2:V_1$) for mature black spruce were available from another study (Salonius et al. 1982). The equation which described the relationship between $R_2:R_1$ and $V_2:V_1$ for unfertilized trees is as follows:

$$V_2:V_1 = 0.193612 + 0.804771\ R_2:R_1 \qquad (r^2 = 0.7).$$

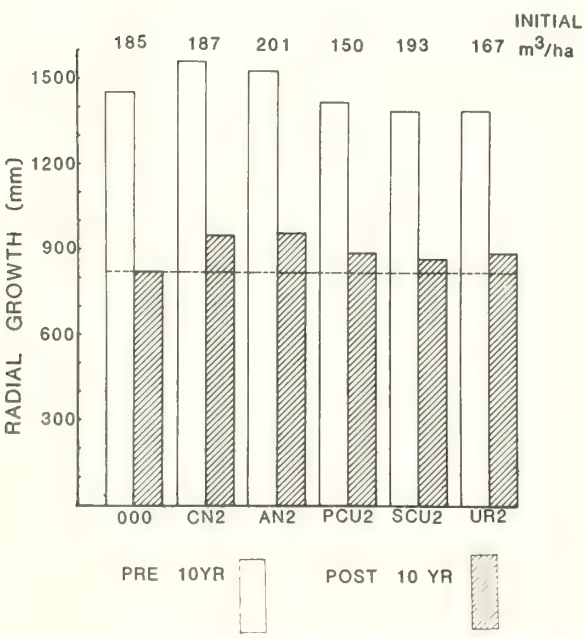

Figure 2.--Total radial growth of surviving black spruce at breast height in the 10 years before fertilization and in the 10 years after treatment. Initial volume on trees that survived until final measurement in 1980.

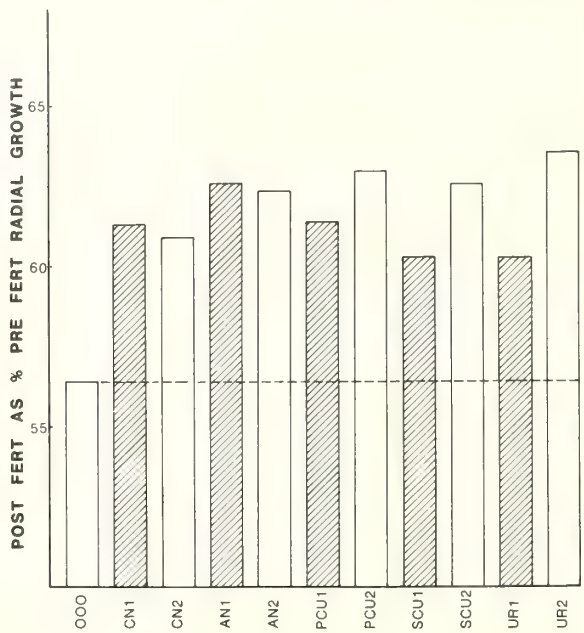

Figure 3.--Postfertilization summed radial growth as a percentage of prefertilization summed radial growth for surviving black spruce.

As V_2 (posttreatment volume growth) (fig. 1) and $R_2:R_1$ (fig. 3) are known for the unfertilized condition in this study, we used the equation to solve for V_1 (pretreatment volume growth) for the control. Using this value (43.49 $m^3 \cdot ha^{-1} \cdot 10\ yr^{-1}$) in the equation and the various radial growth ratios from the fertilizer treatments, we were able to calculate how much volume the unfertilized trees would have grown if they had been fertilized with the various treatments.

The presentation of volume growth in excess of control volume growth for both the conventional method and the alternative method which utilizes radial growth ratios is shown in figure 4. This presentation allows comparison of the results of the two mensurational methods on the basis of the same measurement parameter (volume response). The alternative method showed that nitrogen fertilization tended to increase the volume growth of this black spruce stand consistently, but analysis of variance showed that these increases were not statistically significant.

According to the results generated by the alternative radial growth ratio method (fig. 3 and fig. 4), the response produced by the two nitrate-containing fertilizer treatments was not affected by fertilizer application rate. This may be indicative of heavy leaching losses of nitrate from the rooting zone or due to the phytotoxic products of reactions of nitrate fertilizers in the organic horizons (Mahendrappa 1974). The ureas (plastic-coated, sulfur-coated, and conventional) all produced a greater response at the high dosage rate. The possibility that high rates have completely satisfied soil microbial nitrogen demand (Salonius 1972, Salonius and Mahendrappa 1975, Salonius and Mahendrappa 1979), leaving the remainder available for other avenues of loss and root uptake, may explain the increased response to the higher rates. We have calculated that for this stand the lower application rates with each fertilizer type have produced higher responses in terms of wood volume in excess of control growth per hectare per kilogram of nitrogen applied.

The plastic-coated material was in the form of 6- to 8-mm-diameter prills, and release was generally complete by late fall of the treatment year. Microsites around these large particles thus had a heavy treatment of ammonium ions over the growth season as urea was slowly released from the prills and hydrolyzed by the soil microflora. Among the ureas at the lower level of treatment the plastic-coated material appears to have some advantages. Sulfur-coated urea was in the form of 2- to 3-mm-diameter prills and considerable amounts of this material were still present as intact coated prills in the second growing season (1972); 5 years after fertilizer application a few intact sulfur-coated urea prills could still be found about 2.5 cm deep in the organic soil layer where they act as an indicator of litter accumulation since treatment. Generally, these results do not indicate a tremendous advantage to using controlled release urea formulations. Plastic coating at the lower treatment level produced the best economic response (kg N/m^3) among the urea treatments. Ammonium nitrate at the lower dosage rate produced the best economic response overall (49.3 kg N/m^3).

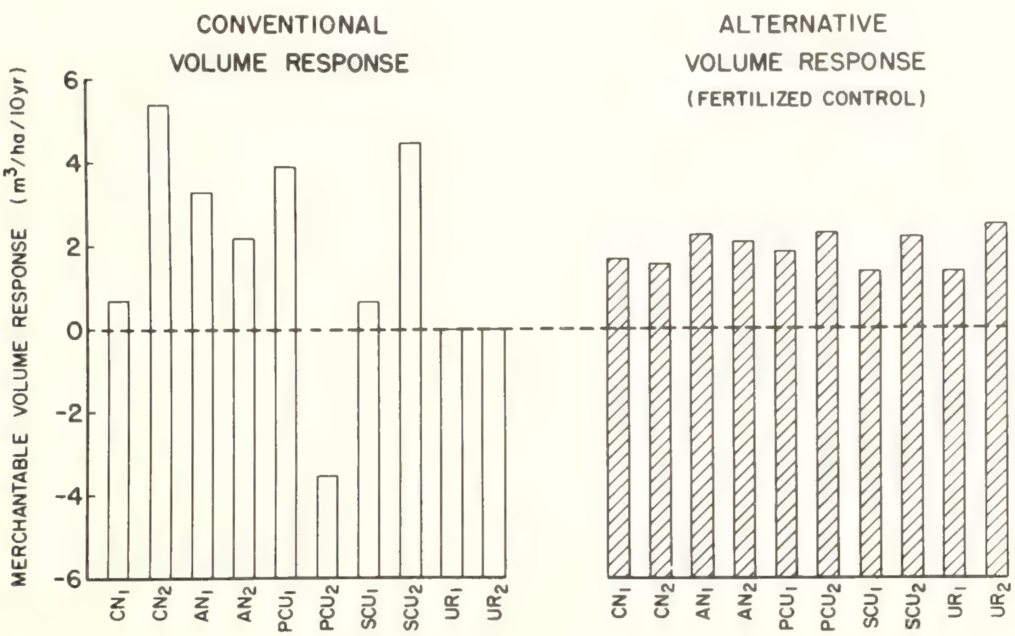

Figure 4.--Volume growth response for the conventional method and for the method that uses radial growth ratios on treated plots to calculate how unfertilized trees would have grown if they had received the various fertilizer treatments (control = 0).

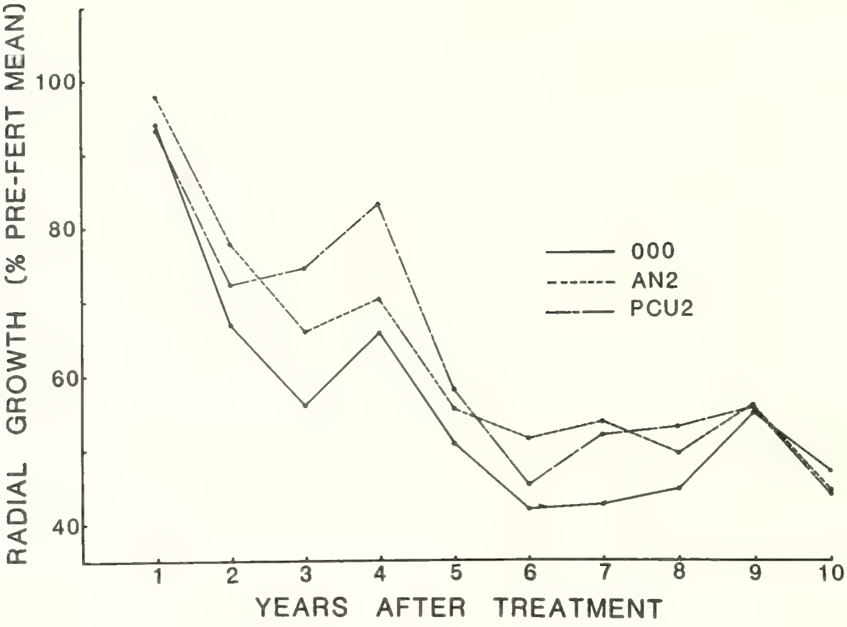

Figure 5.--Annual postfertilization radial growth as a percentage of 10-year mean pretreatment radial growth for surviving black spruce.

In figure 5, we present the annual postfertilization radial growth for the control and two treatments as a percentage of the mean (10 years) pretreatment radial growth. The delayed response of the plastic-coated preparation of urea, as compared with the early response to ammonium nitrate, can be seen.

CONCLUSIONS

Generally the response of this semimature stand to fertilization showed that growth could be enhanced by applying nitrogen; however, the magnitude of the response would not encourage the use of fertilizer in operational forestry. Further work, using the alternative radial growth ratio method of response measurement with each tree or treatment being its own control, should be carried out in possibly more responsive young stands. Young stands that result from plantation or thinning operations, where mortality is not so prevalent, would appear to be the best candidates for such work in the future.

In this study, we used an alternative method of measuring fertilizer response and avoided some of the pitfalls of the conventional method which does not take into consideration prefertilization growth rates. The alternative radial-growth ratio method as used here, does not take into consideration changes in stem form and height increment because it deals only with radial increment at breast height and volume growth ratios from unfertilized trees. It can however be considered a reasonable first approximation of response. To be more thorough, a complete stem analysis, which is extremely expensive, would be necessary. We feel that there may be instances where combinations of climate and site may require slow-release preparations for forest fertilization, but in this experiment such formulations offered no apparent major advantage.

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WHAT IS NEEDED IN PRODUCTIVITY RESEARCH?

E.L. Stone

ABSTRACT: Increasing values of wood and forest land bring a general interest in maintaining or increasing productivity. This common theme takes on quite different meanings in specific forest regions, however, in response to different climatic or soil constraints, accessibility, management objectives, and availability of investment capital. Accordingly, appropriate or high priority research topics in one region are often irrelevant in another, or even for different ownerships or site qualities in the same region. Unity in productivity research will not be found in common research objectives, concepts or techniques but in broad principles and attention to all factors governing the amount and quality of harvested wood.

Historians generally agree that forest productivity research began with Adam, who had unique opportunities for site-index studies in even-aged stands of many species before his attention was diverted elsewhere. Subsequent progress was slow.

Today, however, forest productivity is a concern in many parts of the world and this conference is but one of several to discuss characterization, maintenance, and improvement of productivity. Nevertheless, for many North Americans our symposium may in future years be seen as a sort of divide in the nature of productivity research.

This continent still has vast forest areas; and these areas differ greatly in standing volume, prospective growth rates, accessibility, owner objectives, and values for non-timber purposes. In consequence, the term productivity is being applied to many unlike concepts and to divergent lines of investigation.

This diversity is evident both in the titles of papers presented at this symposium and in other titles that might have been. Much has been said about fertilization, nutrient gains and losses, and classifying forests and forest lands, all obstensibly in the name of productivity. Less, or nothing at all, has been said about factors such as genetic and physiological controls, water in soils and plants, treatments and actions that unnecessarily impair growth, and agents of mortality and growth reduction that widen the gap between potential and realized yields. Nor have we considered how measures to obtain greater productivity of wood may be reconciled with public interest in other values of forest land.

How, then, can one suggest that such a symposium may stand as a divide in productivity research on this continent? The reason is that the papers presented expose, more clearly than ever before, the increasing separation between two kinds of forests and forestrys. One involves the concepts, classification methods and treatments -- some traditional, some modern -- that apply to great areas of natural or semi-natural forests that will continue to produce a large share of this continent's wood. These are the only kinds of forests with which the majority of North American foresters have had first-hand experience. Two decades ago most "productivity research" was concerned with such forests, excepting plantation studies in the eastern United States. The other kind involves a quite different array of assumptions,

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concepts, and capital-intensive methodologies that are being applied to limited areas of accessible soils in inherently productive climates. As in agriculture, though to a much lesser extent, plants and soils are being modified in the interests of maximizing volume or dollar yields, or insuring wood supplies, resulting in "domesticated" or "cornfield" forests.

This distinction is by no means absolute. Many ownerships include both tended plantations and old-growth or regrowth natural forests. Many foresters, both research and operational, work across such divisions with no great sense of contradiction nor discontinuity. Many silvicultural problems, measures, and models can be seen as applicable, at least in principle, to both domesticated and semi-natural managed forests. Nevertheless, there is a widening distinction between those lands that receive large capital investments for the founding and care of young stands in the interest of wood production and all other lands. The aggregate importance of even small increases in net yield over large areas means that research will continue on the latter. The emphasis on increased productivity per hectare, however, is naturally in some proportion to investment levels.

The first step, then, in assessing needed productivity research is to specify what kinds of forests and what management contexts are being considered.

The second step is to sort out the several meanings of forest productivity and productivity research to bring a measure of common understanding. David Ford pointed out that an economist or corporate manager, a silviculturist, and a production ecologist may each mean something quite different by productivity. He might have added that sometimes each is conditioned to remain cheerfully ignorant of alternative concepts, and that those silviculturists acquainted only with very intensive or very extensive management may have little common ground. Procedures necessary or useful to one may have no significance for the other.

The third step, which follows from those above, is to define the objectives of productivity research. Is it simply to grow more wood, or to grow wood faster, better, of different species, at less cost, or in more accessible locations? Or is it to identify and catergorize prospective growth rates by means of soil, vegetation and climatic criteria? Or, again, is it to grow wood as only one product of some intentional mix of "goods and services" from forest land? In short, one cannot address productivity research needs without attention to the product, the producer, and the economic context.

The emphasis of this and related conferences suggests that we are in some danger of trying to elaborate a science of forest productivity out of the conventional plant and soil sciences with insufficient concern for real-life production systems. A science lacking such concern may well enlist the enthusiasm of many researchers, but is not likely to be either influential or well funded. Of all the papers at the symposium, only one, Graham Will, outlined such a production system from tree improvement to harvesting practices, and that was for the relatively simple case of intensively cultured radiata pine plantations in New Zealand.

It would be useful to have similar sketches for the other species, forest types or intended managements with which other symposium papers were concerned. Without some such explicit framework, how does one assess the relative significance to productivity of research in such things as site classification, fertilization, or site preparation impacts as opposed to that in improved planting, better harvest practices, or reduced losses from insects, decay, animals and weeds? For example, many of us have seen well-designed fertilizer trials in forests where, predictably, the only significant contributions to realized productivity would be improved salvage rate and regeneration success after budworm mortality.

Turning to the narrower topics of plant and soil, we might paraphrase Will Roger's declaration that "It ain't people not knowing things that cause so much trouble. It's people knowing things that ain't so." Many supposedly factual generalizations about soil and soil-plant relationships arose solely as convenient hypothesies at a particular place and time and are untested elsewhere.

To such trouble may be added that of scientists using misleading measures for lack of a better, only to be themselves misled by the results obtained. Examples are cation exchange capacity determined at pH 7 for strongly acid soils, bulk density as an absolute measure of compaction, and soil nutrient assessment based on uncalibrated use of standardized extraction procedures. Such things underlie Philip Sollins oblique warning about the dangers of constructing models based on conventional wisdom or on the outcome of isolated experiments. The large efforts entailed in building and testing general models suggest that their foundations (that is, the validity of initial assumptions, data, and production methodologies) deserve at least as much attention as the superstructures they are to support.

A number of gaps in information and specific research data must be bridged before forest productivity studies can be viewed as a comprehensive and fully useful branch of biological science. The miscellany of illustrations that follows relates only to topics raised at the symposium and might easily be broadened:

Not all forests respond to added nitrogen and those that do are not regulated by nitrogen alone. We have not yet learned how to predict which stands will respond to nitrogen in any consequential way except at the extremes or through numerous well-designed field trials. The same must be said about response to other nutrient additions except as overt symptoms

point to deficiency. Soil and tissue tests are imperfect instruments and require extensive calibration against field trials.

The foregoing is less surprising than might at first appear. We are still far from understanding the nutritional requirements of most major species, as shown by the difference in phosphorus uptake of Douglas-fir and western hemlock discussed by Radwin and Shumway. Even those much-studied guinea pigs of forest nutrition, Scots and radiata pine, and Norway and Sitka spruce, continue to generate much new information.

We are not much better off in respect to exact knowledge of soil processes. Although immense gains in assessing the productive capacity of soils and sites have been made over the past three decades, no one can be satisfied with the present level of knowledge. Detailed soil mapping is slow and costly. Moreover, its utility as a productivity index requires a large additional effort in designing and interpreting soil units. Such effort is commonly inadequate in large-scale mapping enterprises. The resulting frustration among many prospective users is reinforced by the infeasibility of detailed mapping over large wildland areas. These and other considerations, coupled with a reawakened interest in vegetation as a visible and readily mapped indicator of "site", has led to numerous offshoots and alternatives to mapping soil and physiography. Substantial rhetoric, rationalization, and research have been devoted to habitat types, biophysical types, ecosystem types, as appropriate units for mapping large forest areas. Inevitably, such systems are also extended to detailed mapping, with or without attention to specific soil features.

This is not the place to compare the utility of various classification systems as guides to productivity matters. It seems fair to credit both soil mapping and the spectrum of biophysical schemes, as well as various soil-site correlation studies, with vastly increasing knowledge of the variety of soils over which even a single species grows. It is equally fair to say that few classification or mapping enterprises have provided much specific information about the quantities of plant-available nutrients and moisture on which inherent productivity and responsiveness to treatment so largely depend.

Numerous studies of forest productivity, conducted either in conjunction with surveys or quite separately, have been too easily beguiled by operational definitions that are based on preconception, convenience, and limited understanding of soil science. Too often the operational definition of rooting depth, and hence of exploitable soil resources, is established by the investigator rather than the tree. The operational definition of available moisture is by conventional and convenient laboratory measurements of sieved samples rather than field measurements. The operational definition of nutrient status is usually based on exchangeable or extractable contents in the upper 20- to 100-cm depth with or without attention to total analyses. Neither, of course, provides any basis for predicting response or modeling nutrient circulation and depletion, except at the extreme or when calibrated against fertilizer experiments on the same soils. The current interest in annual nutrient input by rainfall has the merit of exact measurement, if not discrimination as to origin. In contrast, the attempted quantification of annual leaching losses by unconfined lysimetry can be most kindly described as unmitigated disaster, a triumph of operationalism over soil physical principles.

Interactions between stocking and fertilizer response on the one hand, and stocking, diameter growth, and resulting product potentials on the other, are well recognized, perhaps most dramatically in the radiata "clearwood regimes" being adopted in New Zealand and Australia. Apart from radiata pine, Norway spruce, and possibly Douglas-fir, however, there is little knowledge of how fertility should be coupled with density control to produce maximum amounts of the most valued wood.

Likewise, the probability of interaction between genotype and soil fertility level, or other soil property subject to manipulation, is widely acknowledged. Such interaction is a major feature of selection in agriculture but figures rather perfunctorily or not at all in most North American genotype tests.

The large advances in site classification, forest fertilization, and understanding of biomass accumulation encourage a unifying focus on productivity. From the vantage point provided by this symposium, four needs stand out:

1. Recognition that growth opportunities, accessibility, available capital and, on public lands, multiple-use requirements impose very different kinds and intensities of forest management. Research programs must differ accordingly.
2. Better incorporation of other scientific disciplines into productivity assessment and projection. The need for hard evidence from physiology, tree improvement and pest management activities is obvious. Likewise, better means of coping with long-term risks, such as climatic damage and fire, are needed.
3. Much more attention to real-world production systems and to harvestable yields of valued products. Sawmills and plywood plants don't thrive on biomass alone.
4. More throughgoing, less simplistic research on physical and chemical features affecting nutrient and moisture status, and also on their responses to mechanical disturbances and to weather variations.

Surely, no investigator interested in forest productivity need be idle!

Ballard, Russell; Gessel, Stanley P., tech. eds. I.U.F.R.O. symposium on forest site and continuous productivity. Gen. Tech. Rep. PNW-163. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1983.** 406 p.

The symposium reviewed forest productivity including what is meant by productivity and what factors determine the productivity state of any area; modification by forest practices and the subsequent effects on productivity; maintenance and improvement of productivity; and a review of mineral nutrition especially through forest fertilization programs.

Keywords: Forest productivity, production goals (forest), nutrition (plant), fertilizer response.

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The Seen and Unseen World of the Fallen Tree

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Cover: Ant's view of the seedling, moss, lichen, and mushroom cover on the surface of a fallen class III Douglas-fir tree.

The Seen and Unseen World of the Fallen Tree

Chris Maser
James M. Trappe
Technical Editors

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Abstract

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Large, fallen trees in various stages of decay contribute much-needed diversity to terrestrial and aquatic habitats in western forests. When most biological activity in soil is limited by low moisture availability in summer, the fallen tree-soil interface offers a relatively cool, moist habitat for animals and a substrate for microbial and root activity. Intensified utilization and management can deprive future forests of large, fallen trees. The impact of this loss on habitat diversity and on long-term forest productivity must be determined because managers need sound information on which to base resource management decisions.

Keywords: Fallen trees, decay (wood), decomposition, old-growth stands, Douglas-fir, *Pseudotsuga menziesii,* mycorrhizae, soil moisture.

Contents

Prolog

> . . . dying and dead wood provides one of the two or three greatest resources for animal species in a natural forest . . . if fallen timber and slightly decayed trees are removed the whole system is gravely impoverished of perhaps more than a fifth of its fauna.
>
> (Elton 1966, p. 279)

Introduction

Large, fallen trees are unique, critical, dynamic components of old-growth forests (Franklin and Hemstrom 1980, Franklin and others 1981, Maser and others 1979). Each is a microcosm. Harvey and others (1979b) stated:

> Evidence that soil organic reserves, particularly wood, play important roles in maintaining forest site quality emphasizes the need to properly manage woody materials. Thus, the viewpoint that woody residue represents only waste or a fire hazard must be reassessed. Forest users and managers must recognize the benefits, equivalent to long-term fertilization, that woody and other organic reserves contribute to forest ecosystems.

Even a casual observer of present western forests would note the abundance of fallen trees in various stages of decay, whether in a virgin old-growth stand or a recent clearcut (fig. 1). Up to a century ago western stream systems also characteristically contained abundant pieces and aggregations of large, woody debris, but that debris has been systematically removed to improve navigation, flood control, and drainage. We now have the technological capability to remove more and more woody debris from the forest floor. Conversion of forests from virgin to managed status reduces rotation ages from centuries to decades with a consequent reduction in average size of trees and change in wood quality. Forests of the future will have far less woody material contributed to the forest floor than forests of the past, and that material will differ in size and quality from the woody debris that has been historically prominent in forest habitats.

Woody debris is generally removed from streams or forests in the name of economic progress, but what are the short-term and long-term biological consequences? How is habitat diversity affected, and what is the impact on long-term site productivity? Our purpose is to encourage awareness and to facilitate thought on these issues by synthesizing available data on fallen trees in unmanaged old-growth forests. In so doing, we can also identify some research needs. The geographic scope is primarily the Douglas-fir region, but the principles and concepts should apply elsewhere.

Figure 1.—A Douglas-fir recently recruited to the forest floor.

The Seen World of the Fallen Tree

Life on earth, as humans view it, carries but a single certainty, what lives shall die. Life and death are interdependent. In forests, this is readily apparent in the large, fallen trees that are a major component of the forest floor. Although dead, they are an integral part of the living old-growth forest.

Recruitment of Fallen Trees

Fallen trees are recruited to the forest floor by natural catastrophic events, such as windstorms that uproot and blow over whole trees or break their tops (Childs and Clark 1953, Cline and others 1980, Dahms 1949, Falinski 1978, Roth 1970, Ruth and Yoder 1953) (fig. 2). Heavy snow also breaks out treetops; and avalanches, mass soil movements, and floods knock down whole trees (Rothacher and Glazebrook 1968). Snags—dead, standing trees—on the other hand, usually deteriorate and simply collapse (Boyce 1923, Boyce and Wagg 1953, Cline and others 1980, Graham 1982, Keen 1929) (table 1, figs. 3 and 4).

Figure 2.—Fallen trees are natural components of the forest floor in unmanaged forests.

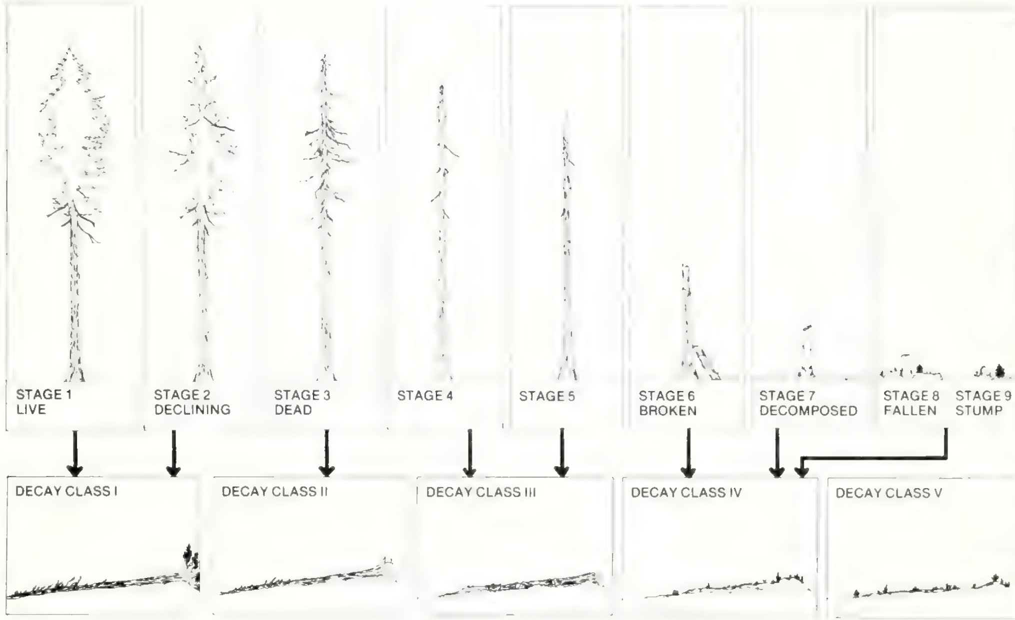
Figure 3.—Snags are also natural components of the unmanaged forest.

Table 1—Stage and condition of snag by decay class of fallen tree[1]

Snag stage and condition	Decay class
1-3, hard snag	I
4-5, hard snag	II
5-6, soft snag	III
7, soft snag, 70 + percent soft sapwood	IV

[1] Adapted from Maser and others (1979).

Figure 4.—When they fall, trees and snags immediately enter one of the first four decay classes (modified from Maser and others 1979).



Mass of Fallen Trees

Trees recruited to the forest floor accumulate through time (table 2, fig. 5); accumulation and rate of decomposition vary with the type of forest, slope, and aspect (Franklin and others 1981, Grier 1978, Graham and Cromack 1982, Maser and others 1979). In one midelevation stand of unmanaged 470-year-old Douglas-fir in western Oregon, the recruitment rate was estimated to be 0.49 fallen tree per acre (1.2 trees/ha) per year (Grier and Logan 1978). The decaying Douglas-fir trees represented from 53.4 to 265.4 short tons per acre (120 to 595 metric tons(t)/ha) (MacMillan and others 1977). Franklin and Waring (1980) showed values ranging from 31.2 to 69.4 short tons per acre (70 to 156 t/ha) in stands of widely different ages; their work included both young stands with large, carryover pieces of rotting wood and old-growth forests. Grier and Logan (1978) found that as much as 60 percent of the annual litter fall in a 450-year-old Douglas-fir stand may be woody debris. Sollins (1982) found that coarse woody debris contributed about 50 percent of the litter on a long-term basis. Further, decomposing trees in western Douglas-fir forests represent more volume above ground than is represented by the aboveground woody debris of typical deciduous forests in the Eastern United States (Day and Monk 1974, McFee and Stone 1966, Sollins and others 1980) (fig. 6).

Table 2—Fallen trees in an old-growth Douglas-fir stand, by decay class[1]

Decay class	Fallen trees per hectare	Fallen trees per acre
	Number	
I	27	11
II	15	6
III	31	13
IV	39	16
V	185	75
Total	297	121

[1] Adapted from MacMillan and others (1977).


Figure 5.—Douglas-fir tree, decay class I, fell before the Douglas-fir snag, which entered decay class III.


Figure 6.—Substantial volumes of decomposing fallen trees are typical of old-growth forests in the Douglas-fir region.

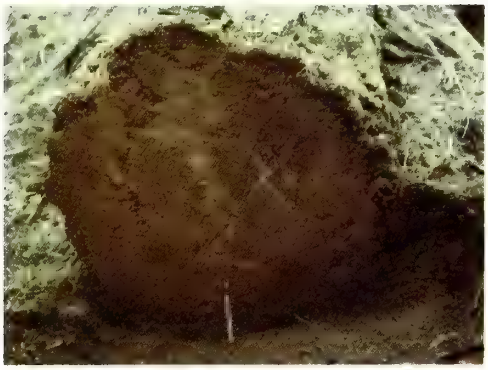


Figure 7.—A fallen tree oriented along the contour of a slope. The upslope side is filled with humus and inorganic material that allows invertebrates and small vertebrates to tunnel alongside. The downslope side provides protective cover for larger vertebrates.

Placement of Fallen Trees

Fallen trees that are oriented along the contours of a slope seem to be used more by vertebrates than are trees oriented across contours, especially on steep slopes. Large, stable trees lying along contours help reduce erosion by forming a barrier to creeping and raveling soils (fig. 7). Soil and nutrients deposited along the upslope side of fallen trees reduce loss of nutrients from the site. Such spots are excellent for the establishment and growth of vegetation, including tree seedlings.

Vegetation becomes established on and helps stabilize this “new soil” (Maser and others 1979), and as invertebrates and small vertebrates begin to burrow into the new soil, they not only nutritionally enrich it with their feces and urine but also constantly mix it by their burrowing activities.

The interactions of fallen trees with soil are directly affected by steepness of slope and ruggedness of terrain; a fallen tree on flat ground, for example, is much more likely to contact the soil over its entire length than is one oriented either across or along contours on steep or rough terrain. The proportion of a tree in contact with the soil affects the water-holding capacity of the wood (Graham 1925). In our studies of fallen trees in old-growth Douglas-fir forests, the moisture retention through the summer drought was best in the side of trees in contact with the soil. The moisture-holding capacity of the wood affects in turn its internal processes and therefore the succession of plants and animals. In addition, the orientation of a fallen tree to aspect and compass direction and the amount and duration of sunlight it receives, drastically affect its internal processes and biotic community (Graham 1924, 1925; Graham and Knight 1965).

Decay Classes of Fallen Douglas-Fir Trees

Dead, fallen trees decay continuously, passing through recognizable stages or classes of decomposition. Fogel and others (1973) described broad classes of decay, based on the physical condition of the bark, wood, and twigs; the presence and pattern of vegetation on a fallen tree and its degree of root development; and the genera of fungi (identified from fruiting bodies or sporocarps) associated with the fallen tree. The five decay classes (Maser and others 1979; table 3), refined by subsequent study (Sollins 1982, Triska and Cromack 1980), are indispensable to research on wood decomposition for three reasons:

1. These stages of decay are inevitable; despite variation in the original material and surrounding environment, a classification of decay based on general processes can be used. (A publication by Minore (1966) can be used to key fallen trees to species.)

2. Decay class can be used without having to determine when the tree fell, a difficult problem that requires destructive techniques.

3. The original decay classes form ecological units that function as distinctive habitats for plants and animals.

The major limiting factor of this decay classification is that it is based on the external characteristics of a fallen tree and does not adequately convey the internal diversity of niches. We have found, however, that internal development of niches relates reasonably well to decay class.

A 450-year-old Douglas-fir stand on the H. J. Andrews Experimental Forest in the Willamette National Forest in western Oregon had a distribution of fallen trees in decay classes II to V that covered an average of 24 percent of the ground surface, ranging from 11 to 35 percent on different subplots. Although class V trees produced the most coverage, many were evident only as mossy or humus-covered mounds on the forest floor. Class I fallen trees, on the other hand, accounted for the least coverage for two reasons: (1) mortality rates are low in old-growth stands (Cline and others 1980), and (2) a rapid rate of decomposition in class I trees quickly converts them to class II. Subsequent change to higher decay classes progresses more and more slowly as the most readily decomposed fractions of the wood are utilized by decomposers (Hulme and Shields 1970).

Variation within and among fallen trees.—One must be aware of two sources of variation when using the decay classification: (1) within a particular fallen tree and (2) among fallen trees of the same decay class.

Variation within a fallen tree.—An old-growth Douglas-fir tapers along the length of its trunk, from its root collar to the tip of its crown (fig. 8). Much of the variation within a fallen tree relates to this taper. The smaller diameter parts of a fallen tree decay faster than the larger ones because the volume of the wood decreases toward the crown, the ratio of sapwood to heartwood increases (Dadswell and Hillis 1962), and fragmentation and contact with the forest floor increase. As decay proceeds, variation within the tree gradually changes; by the time the tree enters decay class V, the entire tree becomes a relatively amorphous, homogeneous mass.

Table 3—A 5-class system of decay based on fallen Douglas-fir trees[1]

Characteristics of fallen trees	Decay class I	II	III	IV	V
Bark	Intact	Intact	Trace	Absent	Absent
Twigs, 1.18 inches (3 cm)	Present	Absent	Absent	Absent	Absent
Texture	Intact	Intact to partly soft	Hard, large pieces	Small, soft blocky pieces	Soft and powdery
Shape	Round	Round	Round	Round to oval	Oval
Color of wood	Original color	Original color	Original color to faded	Light brown to reddish brown	Red brown to dark brown
Portion of tree on ground	Tree elevated on support points	Tree elevated on support points but sagging slightly	Tree is sagging near ground	All of tree on ground	All of tree on ground
Invading roots	None	None	In sapwood	In heartwood	In heartwood

[1] Adapted from Maser and others (1979).

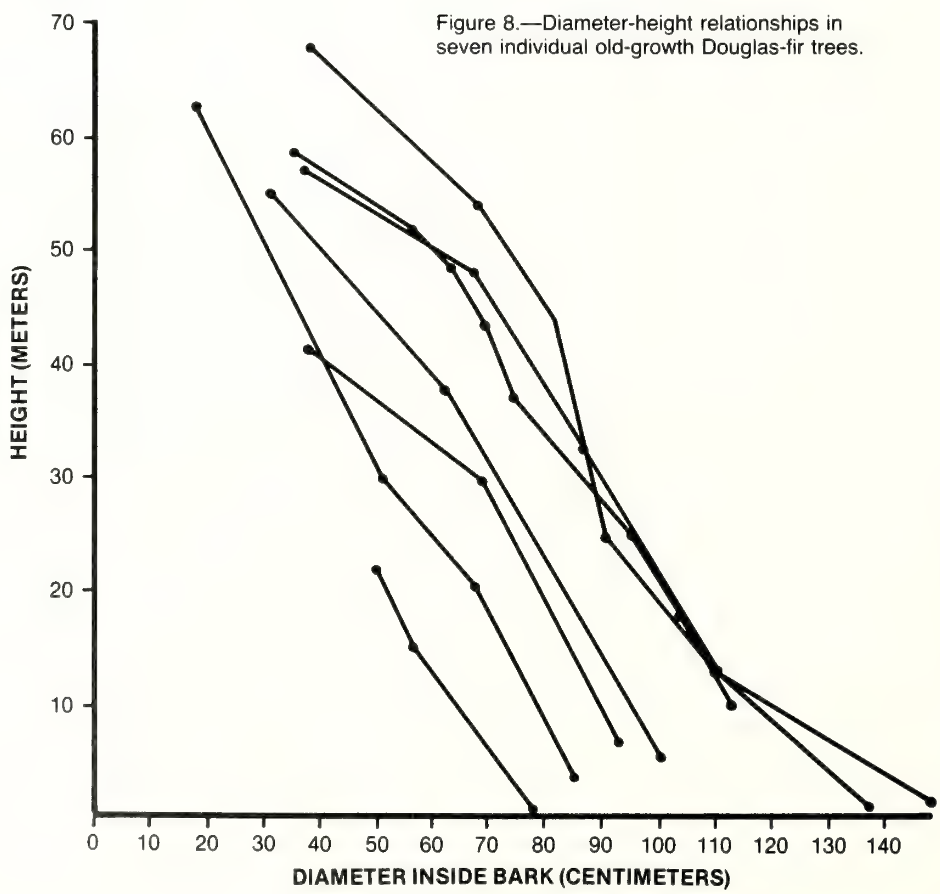


Figure 8.—Diameter-height relationships in seven individual old-growth Douglas-fir trees.

Variation among fallen trees.—The second source of variation—among fallen trees of the same decay class—is partly a consequence of classification itself. A single decay class necessarily contains a variety of fallen trees because they are assigned to a discrete class from a decay continuum. Additional variation, however, is caused by differences among trees at the time they fall. For example, trees vary in size, original diameter, age, old growth versus young growth, decay condition, live tree versus standing dead tree, and presence of heart rot.

A Fallen Tree's Relationship With Time

The age of a fallen tree—the number of years it lies on the forest floor—is positively correlated with decay class, but the relationship is logarithmic rather than linear. The time lapse between classes IV and V is exponentially greater than between decay classes III and IV, and so on. Decay classes I and II evolve rapidly, whereas the later classes develop slowly; variation in residence time within a decay class increases in the later classes. Estimating the residence time or age of a fallen tree becomes increasingly difficult as decay proceeds. Further, decay classes can evolve at different rates, depending on the physical setting of a forest stand, such as a north-facing slope versus a south-facing slope, or low elevation versus high elevation.

Determining the Age of a Fallen Tree

The time a fallen tree has rested on the forest floor can be determined by two standard methods: (1) aging the scars left on adjacent, living trees that were hit by the tree when it fell, and (2) aging the oldest tree growing on the fallen tree (fig. 9).

Scars.—Although aging scars left on the living, woody vegetation by the tree as it fell is the most reliable way to age what is now the fallen tree, such scars are often difficult to locate because they heal over or are inaccessible. Moreover, the healing pattern of wounds varies greatly, so increment cores taken around scars often produce inaccurate estimates of residence time.

A more reliable, but destructive, method of aging is to saw either a wedge or a complete cross section from the scar area; however, sawing injures or kills trees, an intolerable effect on long-term research sites.

Figure 9.—Western hemlock tree and seedlings (background) growing on a fallen tree that has decomposed into a mound on the forest floor.

Seedlings.—The second method of aging a fallen tree is to age the seedlings growing on it. Aging seedlings is a less reliable method than is aging scars because the lapse of time between the fall of a tree and the establishment of the oldest seedling is not known. But this lag can be calculated for a fallen tree by determining ages for both the scar and the oldest seedling and then subtracting the latter from the former. Several pairs of these age counts will reveal the mean lag for the stand. Mean lag can vary markedly from one stand to another.

Age for fallen trees that did not produce scars but do support rooted seedlings can be calculated by adding the mean lag to the age of the oldest seedling. This method of aging fallen trees, however, also requires the sacrifice of living trees that may be important in the development of a stand or in future studies.

Size and Shape of Fallen Douglas-Fir

There are three major sources of coarse woody debris in an old-growth Douglas-fir forest: (1) uprooting of live trees, with or without complete crowns; (2) breakage of crown and stem of live trees; and (3) breakup and fall of snags (Graham 1982). Because size of trees and the manner in which woody material comes to be on the ground vary widely, the resulting pieces of woody debris are heterogeneous in size and shape. Regardless of its original size, wood passes through the various stages of decay; the smaller it is, the faster it breaks down and disappears.

Surveys of large, coarse woody debris in old-growth forests show that broken, fallen trees are typically more abundant than whole fallen trees are (fig. 2).[1] To illustrate the changes in the size and shape of fallen Douglas-fir trees during the decomposition process, however, we will use a generalized whole, uprooted tree with a complete crown as an example.

Volume.—The first noticeable decrease in the volume of a fallen tree is in decay class III (Graham 1982). Bark alone can account for about 20 percent of the volume of a fallen Douglas-fir (Snell and Max 1981). As the sapwood is consumed and fragmented by both plants and animals and sloughs off, about 50 percent of the volume is lost, most of it during the transition from decay class III to decay class IV. This transition is called the basic fragmentation stage because of the cubical chunks of throughly brown-rotted heartwood. Fragmentation continues in decay class V, but the wood is held together by the prolific rooting of plants (fig. 10). Consequently, only 20 percent of the volume of a decay class V tree is lost; but with the loss of that 20 percent, only a tenth of the fallen tree's original volume remains (Graham 1982).

The bark and wood that slough off a rotting fallen tree accumulate alongside the tree. This material forms a mulch that extends over the ground area influenced by the tree.

Diameter.—The diameter of a fallen Douglas-fir decreases as the outer bark, sapwood, and heartwood slough off. So most of the overall volume loss is in diameter rather than in length; in our studies, the transition from decay class III to IV, when the maximum volume is lost, corresponded to the largest reduction (44 percent) in diameter. By decay class V, 68 percent of the original diameter has been removed through decomposition (see footnote 1). Some of the "lost" material is still present as crumbly fragments of wood and bark on the soil adjacent to the fallen tree, and some is incorporated into the soil by animal activity. Some has been physically removed by weather or animals, and some has been used as food by decomposer organisms.

[1] P. Sollins and S. P. Cline. Unpublished data on file at Oregon State University, School of Forestry, Department of Forest Science, Corvallis, Oregon 97331.

Figure 10.—Prolific rooting of western hemlock saplings on a decay class V fallen tree holds the rotten wood together; ground cover is Oregon oxalis.

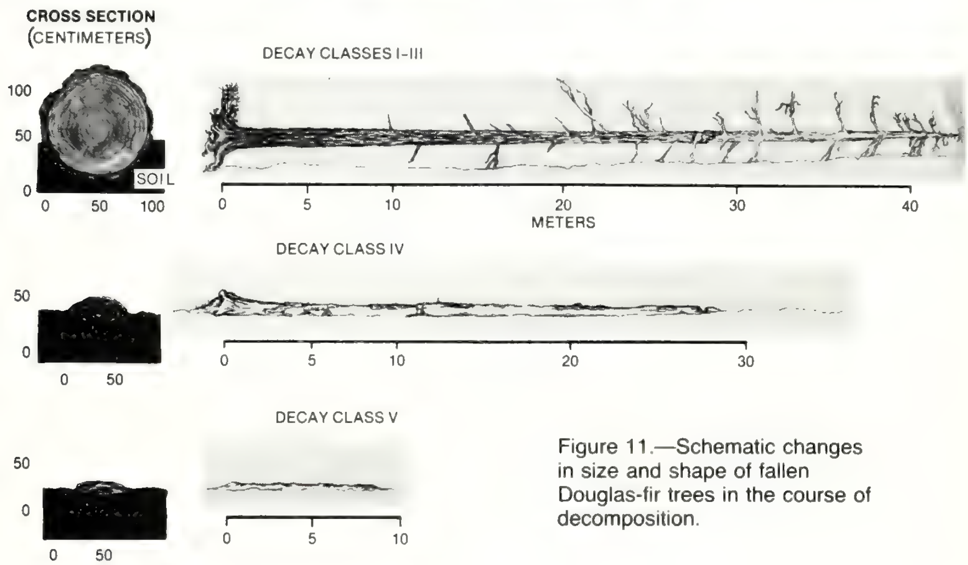


Figure 11.—Schematic changes in size and shape of fallen Douglas-fir trees in the course of decomposition.

A diameter of about 12 inches (30 cm) seems to be a critical boundary between slow or rapid decay and disintegration of fallen trees. Pieces smaller than that have a higher proportion of sapwood to heartwood and disappear more rapidly than pieces of larger diameter. This relationship between diameter of fallen trees and speed of decomposition has important ramifications in managed forests in which total tree size will be controlled.

Length.—The length of a fallen Douglas-fir tree decreases over time from the top toward the roots because the top has the smallest diameter and decomposes fastest (fig. 11). Little change in length takes place in decay classes I through III. By the time a tree reaches decay class IV, its length has been reduced about 15 percent because the top has begun to be incorporated into the soil. The largest reduction in length (about 40 percent) occurs during the transition from decay class IV to V, because the diameter decreases through fragmentation. Therefore, only a fraction of the original length of a fallen tree remains by the time it reaches class V (see footnote 1).

Shape.—Viewed from above, an intact, fallen tree changes in shape from a frustum (a truncated cone, tapered at the top) in decay classes I through III (fig. 5) to nearly cylindrical (both ends with a similar diameter) in decay classes IV and V. This change in shape can be demonstrated by comparing the ratio of basal diameter to top diameter: decay classes I and II = 5:1; decay class III = 4.4:1, decay class IV = 2.1:1; and decay class V = 1.6:1 (see footnote 1).

In a cross-sectional view, a fallen tree is circular in decay classes I through III. By settling and sloughing, it becomes elliptical in decay class IV. The elliptical shape becomes exaggerated, approaching a lens shape, in decay class V and later stages.

Substrates as Niches

Every living conifer is composed of tissues that perform specific functions. When a tree dies, the various tissues provide distinguishable substrates that provide different niches.

The four major tissues of a Douglas-fir tree are outer bark; inner bark or phloem; sapwood, the living portion of the xylem; and heartwood, the dead portion of the xylem (fig. 12). A class I fallen Douglas-fir is mostly xylem, heartwood (60 to 80 percent) and sapwood (5 to 20 percent). The thick, outer bark of an old-growth Douglas-fir may be 5 to 20 percent of the cross-sectional area, whereas the inner bark is usually less than 5 percent.

The outer bark and heartwood of a Douglas-fir tree are physiologically inactive. Outer bark forms a physical and chemical barrier between the inner tree and the atmosphere, insects, and diseases. Heartwood supports the tree and stores metabolic wastes (Brown and others 1949, Hillis 1962). The inner bark and sapwood are physiologically active. Inner bark is the growing portion of a tree and is the site of both formation of new cells and transportation of food, whereas sapwood transports and stores water and dissolved mineral salts (Brown and others 1949).

Decay rate	IB	>	SW	>	HW	>	OB
Soluble carbohydrates	IB	>	SW	>	HW	>	OB
Taxifolin content	IB	<	SW	<	HW	<	OB
Nitrogen content	IB	>	OB	>	SW	>	HW
Mineral content	IB	>	OB	>	SW	>	HW
Water content	SW	>	IB	>	OB	>	HW
Lignin content	OB	>	IB	>	SW	≥	HW
Total extractives	OB	>	IB	>	HW	>	SW
Cellulose content	HW	>	SW	>	IB	>	OB
C:N ratios	HW	≥	SW	>	IB	>	OB
Density	OB	≥	IB	>	HW	>	SW

Figure 12.—Relative decay rates and composition of different substrates of fallen trees: OB = outer bark; IB = inner bark; SW = sapwood; HW = heartwood (adapted from Clermont and Schwartz 1948; Gardner and Barton 1960; Graham and Kurth 1949; Hergert and Kurth 1952; Kurth 1948, 1949; Kurth and Chan 1953; Scheffer and Cowling 1966; and this study).

These parts of the fallen tree provide substrates of differing quality for use by other organisms. Quality of the substrate depends on physical and chemical properties; the higher the quality, the faster it disappears through respiration and fragmentation (Lamber and others 1980). Respiration is the enzymatic transformation by decomposer organisms of organic compounds to carbon dioxide, water, and other simple products. Fragmentation occurs when the substrate is eaten, sloughed, and leached.

The main chemical differences among substrates are: (1) nitrogen content; (2) the mineral or ash content—phosphorus, potassium, calcium, magnesium; (3) the carbon matrix—cellulose, lignin, pentosans (Lewis 1950); and (4) the content of other organic compounds—waxes, pigments, carbohydrates, fats, resins, phenolic compounds (Graham and Kurth 1949, Hergert and Kurth 1952, Kurth 1948).

Many chemical substances are associated with the carbon matrix but are not chemically bonded to it. Bark contains more such extractable materials than wood does (Kurth 1948, 1949) (fig. 12); for example, taxifolin, a natural component of Douglas-fir, has fungicidal properties (Kennedy 1956).

Tissues that were physiologically active in the live Douglas-fir decay most rapidly after the tree falls because they are higher in quality than inactive tissues are (fig. 12). Inner bark and sapwood of freshly fallen trees attract the initial decomposers—beetles that feed on these tissues. By penetrating the protective outer bark, the beetles open the inner bark and sapwood to invasion by other decomposers. These tissues contain more soluble carbohydrates, more moisture, and less taxifolin than do the lower quality outer bark and heartwood (fig. 12). The substrate of poorest quality is the decay-resisting outer bark, which is low in moisture, carbohydrates, cellulose, and carbon to nitroger (C:N) ratio but high in lignin, taxifolin, total extractives, and density (fig. 12).

Regardless of substrate, changes develop during decay of fallen trees: (1) density decreases; (2) water content increases until decay classes III and IV are reached, at which time the water content stabilizes; (3) mineral and nitrogen contents increase; (4) the cellulose content decreases; (5) the relative lignin content increases; and (6) the C:N ratio decreases (Fogel and Cromack 1977, Foster and Lang 1982, Graham and Cromack 1982, Grier 1978, Lambert and others 1980, Sollins 1982).

Inner bark disappears fastest because it has the highest substrate quality and the smallest volume. Both sapwood and outer bark disappear by decay class IV, but for different reasons. Sapwood elicits high biological activity and disappears because of insect consumption and microbial breakdown (fig. 13). Outer bark disappears almost solely by fragmentation and sloughing from the top and sides of a fallen tree. Large trees are mostly heartwood when they fall and by decay class IV only heartwood remains; without the initial association with higher quality substrates, such as sapwood and inner bark, heartwood would undoubtedly decay more slowly (see footnote 1). When deca reaches the advanced class V stage, the fallen tree appears as a mound on the forest floor, usually covered with humus and litter or moss and often supporting several to many hemlocks. Much of the crumbly, brown-rotted heartwood remains in place. Tha which has disappeared, however, is not all lost through metabolism of decomposers. Much of it merges into the humus or becomes incorporated into the soil profile (Denny and Goodlett 1956; Harvey and others 1978, 1979b; McFee and Stone 1966).

Figure 13.—The inner bark and part of the sapwood of this decay class II fallen tree have decomposed; the outer bark and heartwood are still intact.

Figure 14.—A fallen Douglas-fir tree in decay class IV, with wood separated into the characteristic angular blocks known as brown cubical rot; this decay stage provides superb rooting substrate for hemlock seedlings.

Internal Surface Area

The importance of internal surface areas is that, through such surfaces, a fallen tree interacts with its environment. A newly fallen tree, for example, interacts only passively with the surrounding forest because its interior is not accessible to plants and most animals. But once fungi and bacteria, which are smaller than the wood fibers, gain entrance, they slowly dissolve and enter the wood cells. And wood-boring beetles and termites chew their way through the wood fibers. Meanwhile, many other organisms, such as plant roots, mites, collembolans, amphibians, and small mammals, must await the creation of the internal spaces before they can enter. The flow of plant and animal populations, air, water, and nutrients between a fallen tree and its surroundings increases as the aging process continues.

Surface area within a fallen tree develops through physical and biological processes. A tree cracks and splits when it falls and subsequently dries. Microbial decomposition breaks down the material in the cell wall and further weakens the wood. Wood-boring beetle larvae and termites tunnel through the bark and wood; this activity not only inoculates the substrates with microbes but also opens the tree to colonization by still other microbes and small invertebrates. Wood-rotting fungi produce zones of weakness, especially between annual rings, by causing spring wood to decay faster than summer wood; and plant roots that penetrate the decayed wood split it as the roots elongate and thicken in diameter. Because of all this internal activity, the longer a fallen tree rests on the forest floor, the greater the development of its internal surface area. Most internal surface area results from biological activity, the cumulative effects of which not only increase through time but also act synergistically—insect activity promotes decomposition through microbial activity that encourages the establishment and rooting of plants.

Most splitting of the sound wood found in decay classes I-III in fallen trees is radial as the wood dries. Later, the weakening of annual rings by the more rapid decomposition of spring wood than summer wood leads to circumferential cracking as well. The blocky structure in class IV and V fallen trees results from brown cubical rot (fig. 14).

Temperature

Gross environmental features regulate temperature regimes. Latitude, elevation, aspect, and vegetation not only set the maximum and minimum temperature of a site but also control the seasonal range in temperature. For fallen trees, the question is twofold: (1) What is the relationship between the temperatures of air, tree, and soil? and (2) How is this relationship modified through the year by characteristics of the tree itself?

Summer data (see footnote 1, p. 8) indicate the following temperature relationships at all elevations sampled: air > fallen tree > soil. The absolute differences were greater at low elevations than at midelevations or high elevations; mean winter temperatures of the air, a fallen tree, and the soil were nearly identical at each elevation.

Substrate temperatures within fallen trees of a particular decay class differ little at a given time and site, but each decay class responds differently to the temperatures of the surrounding air and soil in summer. Measurements (see footnote 1, p. 8) in August showed the following relationship: air = I = II > III > IV = V > soil. These relationships develop because, as decay proceeds, a fallen tree more closely hugs the soil, which buffers it against fluctuations in air temperature. Thus, trees in decay classes I and II are cylindrical and contact the soil relatively little. Trees in class III have sloughed and slumped somewhat, and those in classes IV and V are partially to mostly embedded in the soil.

Moisture

Whole fallen tree.—Three trends are visible in the water-holding capacity of a fallen tree; the same is true for individual substrates—outer bark (OB), inner bark (IB), sapwood (SW), and heartwood (HW):

1. Water content increases with residence time on the forest floor and with stage of decay (fig. 15, sapwood) because of the microbial breakdown of woody substrates that produces water and carbon dioxide; also, microbial activity increases as decay advances. Simultaneously, the water-holding capacity of woody substrates increases as cell walls break down.

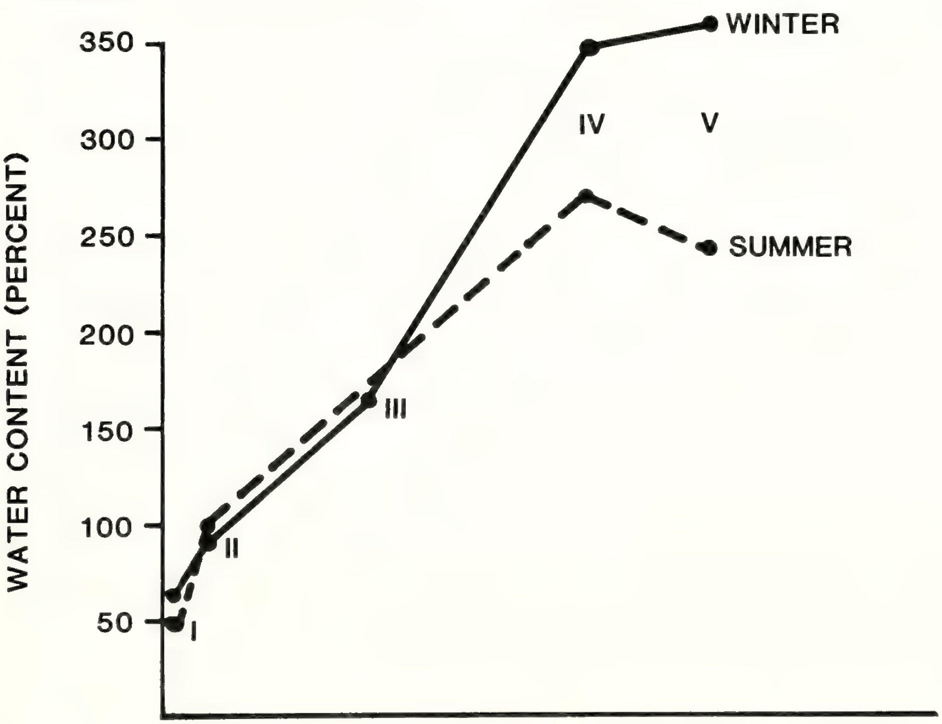


Figure 15.—Water content of fallen Douglas-fir trees in winter and summer; each point represents a decay class from I (newly fallen trees) to V (fallen trees decomposed to a mound of brown cubical rotted wood).

2. In decay classes I through III, the mean water content of fallen trees is nearly equal in summer and winter; but in decay classes IV and V, trees hold more water in winter than in summer. There are two reasons: (1) Winter usually provides abundant water, so the complete storage capacity of the woody substrates is used; and (2) evapotranspiration potential is normally low because days are short, temperatures are cool, and humidity is high.

3. As the overall water-holding capacity of woody substrates increases with stage of decay, so does the seasonal fluctuation of the water content (fig. 15).

Substrates.—Four trends are visible in the water-holding capacity of the substrates within a fallen tree:

1. When a tree falls (decay class I), the water content of the substrates is: IB≥SW>OB>HW. Initially, the inner bark and sapwood (both physiologically active (alive) at the time the tree fell) contain more water than do the outer bark and heartwood (both physiologically inactive (dead) at the time the tree fell). Nearly all of the living cells are located in the inner bark and sapwood of a live tree.

2. The water content of all woody substrates increases during the residence time of a tree and its stage of decay. Again, as with the whole tree, breakdown of woody substrates by microbial activity produces water and carbon dioxide, and microbial activity increases as decay proceeds.

3. The water content of substrates increases at different rates within and among seasons. In winter, for example, water content increases (percent per year): IB>SW>HW>OB. The water retention capacity depends on a given substrate's stage of decay; the more advanced the decay, the more porous the wood and the more water it retains. In summer, however, water-holding capacity shifts in response to exposure of the substrate to evapotranspiration. A fallen tree dries because of the dramatic increase in evapotranspiration brought about by the simultaneous increase in day length and air temperature and decrease in rainfall and relative humidity. The inner bark, for example, is protected from excessive drying because inner bark is sandwiched between the thick outer bark and the relatively moist sapwood. And, being the most nutrient-rich substrate, it supports the highest microbial activity, through which additional water is produced. Heartwood retains water because of its large volume; thus, although the exposed outer surface of a tree may dry, the center retains moisture. Microbial activity continues in the moister areas and produces more water. Outer bark, on the other hand, is prone to drying not only because it is exposed to direct sunlight and wind but also because microbial activity is low, so little water is produced. As the outer bark sloughs off, the sapwood is no longer protected from sun and wind, so it begins to dry out. The drying of sapwood is speeded up because sapwood is more porous than outer bark; therefore, the ability of sapwood to retain water against the forces of evapotranspiration decreases as porosity increases.

4. Seasonal fluctuations of water content increase as the water-holding capacity of the woody substrate increases (fig. 15).

Plant Rooting

Woody plants do not root in fallen trees in decay class I. A tree in decay class II may have plants rooting in its inner bark, which decays fastest of all the substrates; these roots would have reached the inner bark through fissures in the outer bark. By the time a tree reaches decay class III, its inner bark is completely decomposed, and the outer bark and sapwood are often penetrated by roots (in 50 percent of our samples). Only about a third of the heartwood samples in decay class III trees were colonized by roots. When a tree reaches decay class IV, however, only heartwood remains, and nearly all our samples (87 percent) contained roots. Finally, trees in decay class V are not only completely colonized by roots but are actually held together by them (see footnote 1, p. 8).

Within a decay class, plant rooting differs among substrates for two reasons: (1) Substrates decay at different rates, and (2) substrates are not equally accessible to plant roots. In general, as decay proceeds, plant rooting increases in all substrates because they become excellent rooting medium—density and hardness decrease, and water content increases.

Insect Galleries and Frass (Excrement)

Wood-boring insects, such as beetles, carpenter ants, and termites, tunnel within fallen Douglas-fir trees and consume the woody tissues. Their activities are evidenced by their galleries and tunnels often packed with borings and feces. The collective activity of such wood-boring insects appears to be the most important factor in initiating early decomposition of fallen trees—decay classes I-III—for three major reasons.

First, wood is broken down by consumption and digestion by insects and by enzymatic attack by microbes. Insects, however, can penetrate the wood matrix faster than microbes can. Second, consumption and digestion of wood also fragment it. As a fallen tree is fragmented by insect tunnels and galleries, its internal volume is opened to decomposer plants and animals. The wood matrix is reduced to particles (borings and feces), and more surface area is availalbe for microbial attack (Crossley 1976). Third, wood-boring insects serve as vectors for decomposer micro-organisms, such as intestinal inhabitants that are expelled in the feces (Breznak 1982). They are also introduced as external associates; fungal spores, for instance, are transported in special pits and cavities in adult beetles (Francke-Grosmann 1967). Fungal spores and hyphae are also picked up and carried by insect larvae. In addition, each species of insect that tunnels in Douglas-fir bark or wood has its attendant predators, parasites, and scavengers (Deyrup 1981).

Frequency of galleries by decay class of tree.—Studies in the H. J. Andrews Experimental Forest in western Oregon showed that the percentage of wood samples with galleries increased as decomposition of the fallen trees proceeded (see footnote 1, p. 8). When the substrates within a decay class were compared for galleries, they ranked as follows: IB>SW>HW. Outer bark was not included in this comparison because the nature of the galleries differed. Insects simply chew through, not within, the outer bark to gain access to the nutritious inner bark and sapwood. Inner bark disappeared before the frequency of galleries reached 100 percent. But all the sapwood samples had galleries by the time they reached decay class III and the heartwood, by decay class V.

Effects of galleries on wood properties.—Samples of a substrate with insect galleries in a fallen tree were softer and wetter and had a lower density, more plant roots, higher microbial activity, higher nitrogen fixation activity, higher microarthropod populations, and higher exchangeable and mineralizable nitrogen than did samples from the same substrate without insect galleries (see footnote 1, p. 8).

The Unseen World of the Fallen Tree

Decaying trees comprise considerable accumulations of mass and nutrients in unmanaged, old-growth forest ecosystems (Triska and Cromack 1980). Some of the largest accumulations occur in the unmanaged forest stands of the Pacific Northwest. Coarse woody debris can range from 130 to 276 tons per acre (118 to 251 t/ha) in stands from 100 to more than 1,000 years old (Franklin and Waring 1980). Although here we are concerned with Douglas-fir, neither decaying wood nor research data are unique to forests of the Pacific Northwest. McFee and Stone (1966) observed that decaying wood persisted for more than 100 years in New York, and Falinski (1978) noted substantial accumulations of coarse woody debris in an old-growth forest in Poland. Appreciable accumulations of fallen trees also occur in the temperate forests of the Andes of central Chile, in the course of long-term forest succession (Veblen 1979). These observations evidence the long-term continuity of decaying trees as structural components in forest ecosystems.

The decomposing wood of a fallen tree serves as a savings account of nutrients and organic material in the forest soil. Nitrogen, for example, accumulates in decaying trees and branch wood in forests of the Pacific Northwest and other regions (Graham and Cromack 1982, Lambert and others 1980, Lang and Forman 1978, MacMillan 1981, Sollins 1982, Swift 1977b). In old-growth Douglas-fir forests, about as much nitrogen accumulates in decaying, fallen trees as in the forest floor. Other nutrients, such as calcium and magnesium, also accumulate in decomposing woody substrates (Cromack and others 1979, Grier 1978, Rennerfelt and Tamm 1962, Sollins and McCorison 1981, Sollins and others 1980).

Nitrogen fixation by free-living bacteria is another mechanism of nitrogen accrual (Cornaby and Waide 1973, Larsen and others 1978, Sharp 1975, Sharp and Millbank 1973, Silvester and others 1982, Triska and others 1982). Although nitrogen fixation in wood is modest compared with that occurring in other substrates in forests, the persistence of decaying wood allows small increments of nitrogen to accrue over many decades.

Further, decomposing wood undergoes changes in other chemical constituents and pH, as well as in physical structure (Aho 1976, Aho and others 1979, Johannson and Theander 1974, Shortle and Cowling 1978, Tatter and others 1971). Very old, decayed wood can even become somewhat humified and leave a long-lasting substrate resistant to further decay.

Fallen trees harbor a myriad of organisms, from bacteria and actinomycetes to higher fungi. Of these, only some of the fungi might be noticed by the casual observer as mushrooms or bracket fungi (fig. 16). These structures, however, are merely the fruiting bodies produced by mold colonies within the log. Many fungi fruit within the fallen tree, so they are seen only when the tree is torn apart (fig. 17). Even when a fallen tree is torn apart, only a fraction of the fungi present are noticed because the fruiting bodies of most appear only for a small portion of the year. The smaller organisms, not visible to the unaided eye, are still important components of the system.

Figure 16.—Mushrooms of *Inocybe lanuginosa* (Bull.: Fr.) Kumm, a mycorrhizal fungus that fruits only with roots growing in rotten wood.

Figure 17.—*Ceratiomyxa fruticulosa* (Mill.) Macbr., a tiny fungus that typically fruits in cracks within brown cubical rotted wood.

0.5 mm

Microhabitats and Inhabitants

Fallen trees offer multitudes of both external and internal habitats that change and yet persist through the decades. One needs an understanding of the synergistic effects of constant small changes within a persistent large structure to appreciate the dynamics of a fallen tree and its function in the forest ecosystem.

Within fallen trees.—The most obvious changes in fallen trees over time are described in the classification system shown in table 3. The class I tree, mostly intact and undecayed, offers habitat and substrate to only a few primary invaders: bark or wood-boring insects, a few fungi, and bacteria. The entry of these organisms opens the tree to profound changes that render it amenable to many additional tenants. The decayed sapwood enclosed by intact bark in the class II tree provides a soft, fragmented, moist environment much of the year. Many organisms inhabiting the class II tree lose out as decay progresses to class III, when the bark and decayed sapwood slough of Meanwhile, the heartwood becomes increasingly decayed, but the process is much slower than in the sapwood so the class IV stage lasts a long time.

It is in the class IV stage that the fallen tree presents the most diversified habitat and hence supports the greatest array of inhabitants. The decayed heartwood is relatively stable, so plants that become established on it have time to grow substantial root systems. Decayed heartwood splits into chunks; roots grow down the resulting crack as well as along insect channels. Invertebrates—from minute mites to centipedes, millipedes, slugs, and snails—find shelter in these openings and passage along then (fig. 18). Vertebrates, such as salamanders, shrews, shrew-moles, and voles, find cover under debris of sloughed bark and rotten wood alongside the class IV tree; they also find the rotten wood on the underside of the tree crumbly enough for digging tunnels or burrows (fig. 19). Fungi and other micro-organisms abound on the wood itself as well as on the new substrates offered by the feces of animals.

Gradually, the class IV tree breaks down into increasingly smaller crumbles of rotten wood to become class V. The intricate labyrinth of cracks, tunnels, and chambers collapses into a mulchlike mound that is excellent rooting material (fig. 20). It is, however, too homogeneous and unstructured to provide good animal habitat. Because it is no composed primarily of residual materials highly resistant to decay, it does not suppo as diverse a community of micro-organisms as it did in the class IV stage.

Figure 18.—A millipede (*Harpaphe haydeniana*) in a molting chamber made of organic debris under the loose bark of a class III fallen Douglas-fir tree.

Figure 19.—Clouded salamander, an inhabitant of class III fallen Douglas-fir trees in forest openings (photo courtesy of Greg Courtney).

Figure 20.—Two decay class V fallen Douglas-firs in the foreground are decomposed into mounds covered with highlighted Oregon oxalis; the background fallen tree is in decay class IV.

Ultimately, the entire tree is incorporated into the soil. It has gone full circle, having been formed as a product of soil and of photosynthetically captured carbon, it now returns to the soil through release of carbon by decomposition.

Checklists of plants and animals.—There are few checklists of either plants or animals that inhabit fallen Douglas-fir in the Pacific Northwest. No checklist of the micro-organisms in fallen trees of western old-growth forests is available; the subject has hardly been studied. (Higher fungi have been cataloged for many kinds of rotten wood in Europe: Kreisel (1961), Pirk and Tüxen (1957), Ricek (1967, 1968), Runge (1975).) Lawton (1971) listed the mosses that occur on rotten wood or stumps in the Pacific Northwest. Deyrup (1975, 1976) has done a thorough job with the insects and has identified about 300 species associated with fallen Douglas-fir. The only published checklist for vertebrates that use fallen trees is for northeastern Oregon (Maser and others 1979).

Nutrient Cycling

As carryover structural components of old-growth forests, large snags and large fallen trees contribute to the internal cycling of nutrients. Such snags and fallen trees also interact with hydrological cycles and serve as habitat for numerous micro-organisms and higher plants and animals. For example, in one portion of an old-growth Sitka spruce forest in the Olympic National Park, fallen trees covered about 12 percent of the forest floor. A similar proportion of surface area interactions occurs in many old-growth Douglas-fir forests, which resemble some stands in the Olympic National Park (Christensen 1977, Elton 1966, Franklin and Waring 1980, Franklin and others 1981, Grier 1978, Triska and Cromack 1980). Fallen trees in various stages of decay covered 21 percent of the floor of an old-growth Douglas-fir stand in the Cascade Range in western Oregon (Fogel and others 1973).

Fallen trees interact with nutrient cycling processes in a forest through such mechanisms as litter fall (freshly fallen or slightly decomposed plant material from the canopy), throughfall (rain or dew that picks up nutrients as it falls through the canopy), nitrogen fixation, and nutrient uptake by plants associated with the fallen trees. Litter fall and throughfall are major pathways for the flow of nutrients and energy within forests (Carlisle and others 1966, Rodin and Bazilevich 1967, Sollins and others 1980); they contribute nutrients and water to rotten wood. The larger a fallen tree, the more litter it accumulates on its surface and the more nutrient-rich moisture it intercepts from the canopy. The moisture gathers nutrients as it passes through the accumulated litter and soaks into the fallen tree. In addition, a snag may accumulate moisture-carried nutrients and have a higher nutrient capital when it falls than does a live tree.

Ground contact by fallen trees creates opportunities for various interactions with the biotic components of soil and litter. Fungi, for instance, translocate nutrients within the soil-litter system, as both decomposers and root symbionts. Fungi also immobilize translocated nutrients and thereby enrich the decomposing wood substrates they inhabit. In addition, the colonization of decomposing fallen trees by nitrogen-fixing bacteria permits additional nitrogen accretion within the decaying wood (Cornaby and Waide 1973; Dowding 1976, 1981; Larsen and others 1978; Melin and Nilsson 1950, 1952; Silvester and others 1982; Sollins and others 1981; Swift 1977a, 1977b).

Colonization of decomposing wood by animals helps microbes to enter interior surfaces of the wood and creates additional openings for entry of water and nutrients; and penetration of the wood by roots of trees, such as western hemlock, facilitates entry by mycorrhizal fungi (fig. 21). Western hemlocks colonize rotten wood over many decades (figs. 9, 10, and 14) to insure long-term interactions by root zone processes. Decaying wood thus serves as a savings account of soil organic materials and nutrients in forest ecosystems (Christy and others 1982, Graham and Cromack 1982, Kuhnelt 1961, Lambert and others 1980, Swift and others 1979).

Interactions—Nutrients, Plants, and Animals

The continuum of a fallen tree is composed of, and driven by, an increasingly complex network of simultaneously developing minisystems—all interdependent. These minisystems are: (1) animal-plant-nutrient, (2) plant-nutrient, (3) plant-plant, (4) animal-plant, (5) animal-animal, and (6) nutrient-plant-animal-nutrient. The cumulative effect of these systems is far greater than the sum of their parts. Ausmus (1977) stated the impact simply: ". . . wood decomposition represents a long-term stabilizing force within the forest ecosystem."

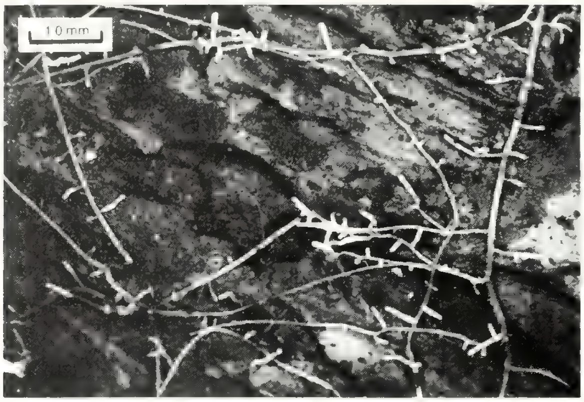


Figure 21.—Small roots and mycorrhizal feeder root tips of western hemlock in rotten wood.

The following simplified scenarios illustrate known facets of each minisystem, and each internal minisystem builds on the preceding one. They are continually being added to, subtracted from, and variously interwoven (Kimmey and Furniss 1943). Some grossly simplified activity levels might be:

1. Animals that eat the fallen tree, which opens it to the outside and initiates nutrient cycling: wood-boring beetles, carpenter ants, termites, and wood-tunneling mites.

2. Micro-organisms that live on the fallen tree: bacteria, yeasts, and ambrosia fungi.

3. Animals that eat live micro-organisms that grow on the fallen tree: collembolans, mites, and ambrosia beetles.

4. Live plants, such as western hemlock or huckleberry, that form a specific symbiotic (mycorrhizal) association with other live plants (particular fungi), both of which are partially or completely rooted in the fallen tree.

5. Animals that depend on the fungal portion of the mycorrhizal association for their food supply: mites, beetles, and the California red-backed vole.

6. Animals that eat live animals: mites, spiders, pseudoscorpions, centipedes, and salamanders.

7. Animals that eat detritus (dead plant and animal material and animal feces): earthworms, mites, millipedes, isopods, and earwigs.

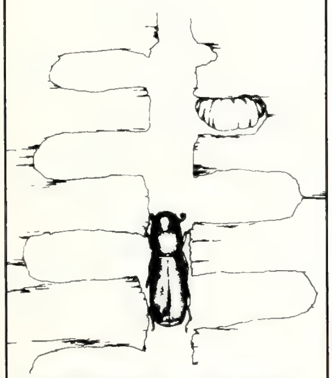
Trees fall on the forest floor in various stages of decomposition, from sound windthrown trees to snags to stubs of old snags toppled because they are so badly decayed that they can no longer support themselves. Each is unique when it begins its new "life" as a fallen tree. Some of the decay organisms living in standing trees in an old-growth forest may continue their activity after a tree falls. Others, especially those that were in the tops of the standing trees, soon die out after the tree falls and are replaced by ground inhabitants. In the following discussions, we describe the events and organisms in live trees that were windthrown. Fallen snags or stubs are recruited at more advanced stages of decay.

Bark beetle

Animal-plant-nutrient.—Tree bark is such an effective protective barrier that the first minisystem to develop in a new, class I fallen tree is the animal-plant-nutrient minisystem. For example, a bark beetle (Scolytidae) (an animal) chews through the bark and thus connects the outside world with the inside of the tree. As the beetle enters and begins to use the tree, it not only introduces fungal spores but also initiates the nutrient cycle with its first deposit of bodily waste.

The character of the available food is decidedly varied in the different parts of a newly fallen tree. Proteins are concentrated in the living tissues (phloem—the inner bark and cambium); carbohydrates, on the other hand, are concentrated in the dead woody tissue (xylem). In addition, the living inner bark and cambium are more easily digested than is the sapwood; but the moist sapwood is more digestible than the drier heartwood. So each portion of a fallen tree supports a characteristic group of insects adapted to a specific set of circumstances. Further, the numbers of a given species are regulated by the availability (quantity and quality) of their food supply. Since the inner bark and cambium furnish the most nutritious food, this microhabitat is promptly occupied. The area of next importance is the sapwood, then the heartwood, and finally the bark (Anderson 1960, Graham 1925).

The insects occupying the live inner bark and cambium must be able to chew or bore their way through the dead outer bark and are called borers. There are two groups: (1) those that spend all their developmental or immature stages in this substrate and (2) those that spend only part of their developmental stages in this substrate (Anderson 1960, Graham 1925).



Bark beetle in egg gallery

The first group is typified by a bark beetle. For example, the Douglas-fir beetle breeds in both live trees and class I fallen trees that result from windthrow. Because these beetles depend on the fresh, green tissues of the inner bark and cambium, they must develop rapidly before their perishable habitat and food supply dry out or become chemically and physically altered by other organisms.

A female Douglas-fir beetle attacks class I wood in early spring by chewing through the outer bark. When she reaches the inner bark and cambium, she chews an egg gallery that is usually 2 feet (60 cm) or more in length along the axis of the tree. The egg gallery is about one-quarter of an inch (6 mm) wide and has small "grooves" on alternate sides; 10 to 36 eggs are laid together in the grooves. When the eggs hatch, the larvae chew lateral feeding galleries through their food supply—the phloem. As the larvae grow, the feeding galleries increase in size. Larvae pack their feeding galleries with borings (refuse) and frass as they eat. The larvae dine throughout the spring, summer, and autumn. In autumn, a larva creates a pupal cell at the end of its feeding gallery where it overwinters as a mature larva. Adults overwinter also and begin to emerge in April. The cycle, from egg to sexually mature adult, requires about 1 year, and one generation is produced annually (Anderson 1960, Chamberlin 1949, Furniss and Carolin 1977, Furniss and Orr 1970, Graham and Knight 1965).

Flatheaded wood borer

The second group is typified by some members of such wood-boring beetle families as Buprestidae (flatheaded or metallic wood borers) and Cerambycidae (roundheaded wood borers). Some flatheaded wood borers, for example, develop in the inner bark and cambium, but others feed there only for a time and then enter the sapwood. Still others go directly into sapwood and heartwood.

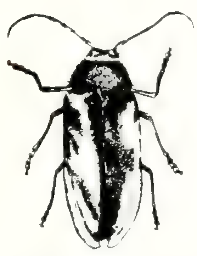
Figure 22.—The golden buprestid prefers the sapwood and heartwood of class I fallen Douglas-fir trees.

A good example of the family Buprestidae is the golden buprestid (fig. 22). The golden buprestid feeds briefly in the cambium but prefers the sapwood and heartwood of class I wood. It will, however, inhabit partially to completely seasoned wood.

A female deposits her eggs in flat masses wedged in crevices in the bark or in cracks in exposed wood. The young hatch and immediately start boring into the wood. Their oval tunnels increase in size as the larvae grow. The tunnels range in length from 3 to 15 feet (0.91 to 4.6 m) from where the eggs hatch to where the larvae mature. As they feed and grow, the larvae pack their tunnels with borings and frass. The larvae mature in 2 or more years, construct pupal cells near the surface of the fallen tree, overwinter, and emerge in spring as adults. Before laying eggs, the newly emerged adults feed on needles of Douglas-fir, then find a class I fallen tree and start the cycle again.

Although the normal life cycle of the golden buprestid from egg to mature adult is usually 2 to 4 years, the length of the cycle is influenced by the quality of a larva's habitat. In poor quality habitat, the life cycle may take a decade or two (Anderson 1960, Chamberlin 1949, Furniss and Carolin 1977).

Within the family Scolytidae is a group of bark beetles called ambrosia beetles that live primarily in the sapwood of class I trees. They are unique among the wood-boring insects in that they do not eat the wood, so the borings are cast out of the tunnels where they collect on the surface of the bark or wood as light-colored powder. Adult beetles, depending on the species, construct a variety of tunnels as follows: (1) an open cavity; (2) a long, winding, branched or unbranched cylindrical gallery in which larvae move about freely; and (3) a compound tunnel, in which "larval cradles" or small pockets are chewed, at right angles, along the main channel (Barras and Perry 1975, Francke-Grosmann 1967, Furniss and Carolin 1977). Ambrosia beetles, especially the females, store certain fungi in specialized structures called mycangia. The fungi, called ambrosia fungi, are introduced into the beetles' galleries during the beetles' burrowing. Particular species of fungi are host specific to certain species of beetles. As the fungi grow, they are eaten by both the adults and the larvae. The beetles' requirements, however, are very exacting; if moisture conditions in the galleries are unsuitable, the crop of fungi either fails and the beetles starve or the crop explodes and the beetles smother in their own food. Hence, the stage of decomposition of a fallen tree is critical (Furniss and Carolin 1977).



Ponderous borer

The ponderous borer (family Cerambycidae), the largest western cerambycid, directly penetrates the sapwood and heartwood. Adults emerge during the summer. After they mate, a female deposits her eggs in crevices in the bark or in cracks in exposed wood of class I fallen trees. The eggs hatch and the larvae chew their way into the sapwood and then deep into the heartwood of the tree. They grow to nearly 3 inches (7.5 cm) in length by the time they are mature; one generation requires 3 to 7 years to mature. The oval, meandering galleries of mature larvae are large (1 to 2 inches (2.5-5.0 cm) in cross section) and are filled with frass and refuse. When they are mature, larvae construct pupal chambers at the ends of their feeding tunnels and pupate. They emerge as adult beetles in summer, mate, lay their eggs, and die (Anderson 1960, Chamberlin 1949, Furniss and Carolin 1977).

Another penetrator of fallen trees is the carpenter ant. The abundance of dead wood in an old-growth forest provides numerous sites for queen carpenter ants to establish new colonies, but as these sites deteriorate, the queens die, and the weaker colonies subsequently become decadent and also die. Although fallen trees, stumps, and the bases of snags serve as initial nesting sites, they are not permanent. "Permanent" nesting sites are provided by living trees. The reproductive success of carpenter ant colonies is related to the age of the colonies, and large (old-growth) trees provide permanent nesting sites. When a nesting site finally deteriorates, a strong ant colony can move to another site and withstand catastrophes that would eliminate a weak colony (Sanders 1970).

In brief, the carpenter ant's life history is as follows: the young males and females leave the nest in early spring and, being winged at that time, disperse in all directions. The air is sometimes filled with these flying ants that emerge simultaneously from many nests in their mating flight (Graham and Knight 1965).

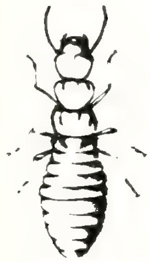
The males die shortly after mating, but the young, mated females may go into old, established colonies to replace decrepit queens or each may establish a new colony. In the latter case, a young queen seeks a small cavity (for example, in a fallen tree) and constructs her brood cell by completely enclosing the cavity, leaving neither exit nor entrance. In this sense, members of the genus *Camponotus* differ from ants of other genera in that a queen works alone in founding a colony (Graham and Knight 1965).

Once the brood cell is complete, the young queen breaks off her wings; they are no longer of use. And after sealing herself in, she does not feed again until her first brood of young is mature. She lays a few eggs that hatch in about 10 days. The newly hatched larvae are fed a secretion from the queen's salivary glands. The larvae complete their development, spin their cocoons, pupate, and emerge as adults about 30 days after hatching. The only food the first brood has during their development is the material from the queen's salivary glands. Although this first brood of workers is small, they take over the work of the nest as soon as they mature (Furniss and Carolin 1977, Graham and Knight 1965).

The workers cut approximately parallel, concentric galleries that run longitudinally through the wood, primarily where it is soft from decay. These galleries are continually increased to accommodate the enlarging colony. The wood is not eaten, as it is by beetles, but is cast out through openings cut to the outside, sometimes called windows. Excavation of the galleries causes piles of wood fiber or sawdust to accumulate below the access holes. Food secured by the workers is also brought into the colony though these openings (Furniss and Carolin 1977, Graham and Knight 1965).

The workers feed the queen, care for the eggs she lays and for the larvae that hatch from the eggs, and feed the larvae secretions from their mouths. The "nurses" continually move both larvae and pupae to the most favorable places within a colony. When young adults are fully developed, the nurses assist them from their cocoons and treat them with the "greatest consideration" (Graham and Knight 1965).

At home in shady, wet places, carpenter ants are catholic in diet. Their menu includes animal food, such as caterpillars of certain butterflies, and sweets, such as honeydew secreted by aphids. Carpenter ants have even been known to shelter aphid eggs in their nests during winter and to carry them out in the spring and place them on plants to develop (Furniss and Carolin 1977). With this exchange of materials, the ants establish a purposeful, physical link between the inside and the outside of a fallen tree.



Termite

By the time a fallen tree reaches late class II, it has a relatively high moisture content, but the wood is still sound. At this stage of decomposition, it is suitable for habitation by the Pacific dampwood termite, which sooner or later colonizes most large fallen trees in the coastal forest (Furniss and Carolin 1977).

Colonies of Pacific dampwood termites contain reproductively active individuals (primary reproductives), soldiers (that are sterile), and nymphs; but they do not have workers. The winged, reproductively active individuals, the most familiar form, sally forth on warm evenings in August, September, and October to mate and form new colonies. Tevis (1953) aptly described the termites' appearance: ". . . on a particular quiet, sultry afternoon . . . shortly before sundown the forest became alive with the wing-rattling of termites streaming from slit-like holes in damp logs and taking to flight."

Typically, colonies are formed by swarms of primary reproductives. Such individuals appear in established colonies and accumulate for a short period before departing on their nuptial, colonizing flights. During the predeparture period, the primary reproductives are sexually immature. Their sexual maturity culminates as they take wing, in about equal numbers of males and females. Termites are weak fliers and seldom travel far without the assistance of a breeze. They are also vulnerable to predators, such as bats. The survivors, on completing their flights, cast their wings. When a survivor encounters an individual of the opposite sex that has also cast its wings, the pair walks in tandem—the male following the female—as they seek a fallen tree in which to excavate a small nuptial chamber and copulate (Imms 1960, Whitaker and others 1977).

Individuals produced during the early stages of colony development are sterile; winged, reproductive individuals develop when a colony is about 4 years old and contains 400 to 500 individuals. Individual termites are long lived (several years), an important factor in permitting a close relationship between successive generations and an important element in the termite's social organization (Imms 1960).

Pacific dampwood termites feed on the rotting wood in which they live. They even appear to be attracted to a specific fallen tree when it is ready for their habitation; its readiness depends on the presence of certain acids and aldehydes produced by particular tree-inhabiting fungi. These substances initially attract termites to a fallen tree and then attract them within the tree to the wood that is appropriate for consumption (Becker 1971).

A termite can digest the wood it eats because of a mutually beneficial, three-way relationship between the individual termite, cellulose-digesting Protozoa, and nitrogen-fixing bacteria that live in its gut. The Protozoa digest the cellulose in the wood and convert it to a form that the termite can use as food. In turn, the termite's body provides an anaerobic chamber that is replete with food for the Protozoa. Wood particles eaten by the termite pass into the chamber and are engulfed by the Protozoa that ferment the cellulose. Major products of fermentation are carbon dioxide, hydrogen, and acetic acid. The acetic acid is absorbed through the wall of the termite's hindgut and is oxidized as energy (Breznak 1975).

Nitrogen is important in the termite's diet, especially because it is required by the cellulose-digesting Protozoa. Wood, the primary ingredient of the diet, is low in nitrogen, although termites consume mostly wood colonized by fungi that probably supply vitamins and some nitrogen (Esenther and Kirk 1974). Whenever the nitrogen intake by a termite is deficient, the nitrogen-fixing bacteria in a termite's gut make up the difference. The nitrogen-fixing activity varies inversely with the amount of nitrogen contained in a termite's diet. The nitrogen-fixing response of the bacteria to changes in dietary nitrogen is rapid. The nitrogen-fixing system is efficient and is potentially capable of quickly supplying a termite with usable nitrogen should its dietary level suddenly drop (Breznak 1975).

The Pacific dampwood termite lives in a series of galleries, eaten in the wood, without any external sign of a colony. Even so, by the time a colony has run its course, it ha greatly altered the interior microhabitats of a fallen tree. The abandoned galleries form a major network of passages used by other animals and through which plant roots find easy access and ready nutrition.

Some mites also eat the well-decomposed class IV wood (Hartenstein 1962, Luxton 1972). A particular group of organisms in fallen trees, immature wood-tunneling mites, preferentially feeds on the fecal material of such organisms as wood borers. These immature mites probably consume wood that has already been chewed and partially digested until they develop an adult's capability of chewing and digesting wood first-hand and can excavate their own tunnels (Wallwork 1967, 1976).

Plant-nutrient.—The succession of plants on fallen trees is mediated by changes in nutrient availability and physical properties over time. Three broad phases can be defined: initial, optimal, and final (Kreisel 1961; Ricek 1967, 1968). Early invaders prepare the tree for later colonization by altering its physical and chemical properties during the initial phase. The altered tree provides the best substrate for a wide array of organisms during the optimal phase. Ultimately, the depletion of nutrients and physical deterioration of the wood during the optimal phase diminish its value for many organisms, so fewer species inhabit the final phase.

The initial phase encompasses class I and early class II fallen trees, those with bark intact and heartwood still sound. The earliest use of a newly recruited tree is likely to be by heart rot or butt rot fungi and associated micro-organisms that inhabited it before it fell. Other organisms quickly enter where its interior is exposed at breaks or splits in the bark. When beetles chew through the bark, they create additional ports of entry. The beetles also carry spores of decomposition fungi that thrive in the beetle galleries, which are excellent incubators filled with nourishment for the fungus and protected by the bark from drying and from temperature extremes. These earliest invaders are opportunistic scavengers—fungi and bacteria that join the insects in exploiting the readily available carbohydrates of cambium, phloem, and sapwood of a recently fallen trunk. As the most easily extracted nutrients are depleted, these early invaders sporulate. The spores are then carried off by the emerging new generation of insects reared from eggs laid after the tree fell.

Meanwhile, free-living, nitrogen-fixing bacteria may be active at low levels in the wood to add to the nitrogen pool available for growth of the wood decay fungi (Aho and others 1974, Larsen and others 1978, Silvester and others 1982). Other nitrogen is added by rain falling through the old-growth canopy, which is rich in lichens that fix nitrogen (Sollins and others 1980); and much of the nitrogen extracted by initial decomposers is still present in their dead cells or in frass, ready to be recycled.

Later in this initial successional phase, the early scavengers are succeeded by fungi more competent in decomposing cellulose and lignin in the sapwood. This process moves relatively fast, as long as the bark hangs together on the fallen tree to preserve the incubator environment within. Furrows in the bark on the upper side fill with leaf litter and provide sites for several years for seeds to germinate. Where the bark is intact, seedlings generally die during summer drought. If a seedling's roots find a crack or hole in the bark and grow into the decomposed layer between bark and wood, however, it may find enough moisture to survive the summer. Western hemlock, huckleberry, and salal commonly become established this way on fallen trees, as do spruces (Christy and others 1982, Eichrodt 1969, Göbl 1968, Minore 1972, Mork 1927). Seedling top growth is generally poor at this successional phase because nutrients are limiting and the roots may not have contacted the mycorrhizal fungi needed for nutrient acquisition (see "Plant-plant"). Root growth, however, may be extensive but it is trapped in the zone of decomposition between bark and heartwood.

A transition from the initial stage to the optimal stage of plant succession on a fallen tree occurs in late class II and class III stages; sloughing of bark is a major event in this transition. When the bark sloughs off, it may take with it some of the plants that have grown through it to form roots in the decaying sapwood. Plants that remain will have much of their root systems exposed to air and sun. As sapwood deteriorates and sloughs off, additional plants are removed with it.

As the tree enters class IV (most bark and sapwood removed), it also enters the optimal stage of plant succession. The heartwood is much decayed, usually as brown cubical rot. Wood thus rotted becomes spongy and tends to separate into angular chunks, and the intervening cracks provide interior surfaces for the fruiting of fungi and for the growth of roots. Insect tunnels provide additional passages for root growth. Mineral content of the fallen tree at this stage may exceed the original content because minerals have been added by litter fall from the canopy and by throughfall of rain, have been brought

in by animals, or have been translocated from underlying soil by fungi or roots. Nitrogen may be added by similar means and by biological fixation (Larsen and others 1978, 1982; Silvester and others 1982). These circumstances provide an excellent rooting medium for plants. A great variety of fungi, both decomposers and symbionts, thrive in the complex of niches within the fallen tree. Lichens, mosses, and liverworts become established on the surface and stabilize it after the sapwood sloughs off. Hemlocks and other plants become established on the upper surface of class IV trees, but their roots grow through it into underlying soil as well as along its length. Nutrients may be acquired from the tree itself or from the soil.

The optimal stage may last for many decades, but in time the fallen tree enters the final, more depauperate stage of class V. It loses structure and shape and becomes increasingly low and covered with forest floor material that buries the lichens, mosses, and liverworts. Roots of overstory trees and of trees that became established in earlier stages now permeate it and bind it together. New plants seldom become established because of the humus cover and the intense competition of roots already there. Relatively few decomposers remain because only the lignins, the most resistant to decay, are left. Mycorrhizal fungi seem to predominate and are the primary fruiters. The moisture content of such material remains high compared with that of soil during summer drought, and roots and fungi can grow actively in it long after most roots in nearby, dry soil have become dormant or desiccated (Harvey and others 1978, 1979a, 1979b; Place 1950).

Plant-plant.—The earliest interactions between plants in the newly recruited, class I fallen tree are between micro-organisms, the initially invading scavengers. Competition for the readily available carbon, nitrogen, and minerals is simple: The first to arrive gets the most. More subtle interactions may also develop between specific organisms; for example, some fungi produce antibiotics that suppress certain bacteria, or volatiles, such as ethylene, that may inhibit some organisms and stimulate others (Graham and Linderman 1980, Marx 1973). Free-living, nitrogen-fixing bacteria may provide some of the nitrogen required by wood-rotting fungi (Aho and others 1974).

As fallen trees progress from decay class I to class II, the scavengers are replaced by competitors with the enzyme systems needed to decompose the more complex compounds in wood. The fungi involved in this activity are often mutually antagonistic, so that a given part of the tree may be occupied by only one fungus that excludes others by physical or chemical means (Li 1981, Nelson 1967).

The penetration of plant roots through openings in the bark of an advanced class II tree introduces new possibilities for fungal or microbial colonization because the roots offer carbon and nitrogen compounds quite different from those of the wood. Some of these compounds may be secreted from the roots to selectively promote growth of certain micro-organisms (Slankis and others 1964, Smith 1969). Some fungi are capable of penetrating feeder roots to tap the nutrients within. Fungi that damage or kill roots in the process are pathogens. Certain fungi, however, grow on and in plant feeder roots as symbionts that not only acquire photosynthetic products from the host root but also provide nutrients, vitamins, and growth regulators to the host. These symbiotic, fungus-root structures (mycorrhizae) are extremely important in colonization of rotten wood by higher plants (fig. 21).

Most plants that grow on rotten wood in old-growth Douglas-fir forests require mycorrhizae to survive; without the mycorrhizal fungi, the host plant cannot acquire adequate nutrients. Western hemlock, spruces, and the Ericaceae are all dependent on mycorrhizae. Hemlock seedlings may survive a year or more without mycorrhizae, but growth is minimal until the mycorrhizal fungi colonize the roots (Christy and others 1982). The fungi must first be introduced into the fallen tree as spores or resting cells; they are transported there by insects, small mammals (Maser and others 1981), wind, rain, or a combination thereof. In a class II tree, the spores need to get through the same openings in the bark used by the plants. They are most likely to be moved through the openings by water or as "hitchhikers" on insects or other arthropods.

Some plants on rotten wood form mycorrhizae when the fungi are available but can also grow without them. Many ferns appear to be in this category (Boullard 1979). A few other plant families, such as the sedge and rush families, rarely form mycorrhizae. None of these are as abundant as the mycorrhizal plants on rotten wood in Douglas-fir forests, perhaps because they are less competitive for the nutrients in rotten wood: Many of the nutrients are in organically bound forms that can be cracked only through action of enzymes not produced by green plants. Mycorrhizal fungi, in contrast, are able to decompose some of these compounds and to translocate the released nutrients to the host (Todd 1979).

As a fallen tree progresses through decay class III, the diversity of plants and associated mycorrhizal fungi may increase, especially if roots grow down through the rotted sapwood into the underlying soil. Sloughing of bark, however, suddenly exposes roots in decayed sapwood to freezing in winter and drying in summer, and many of the fine roots die. As the decayed sapwood sloughs off, plants rooted in it may slough off with it. Even if their roots penetrate partially rotted heartwood underneath, they fall over and often die.

The optimal stage of plant development is attained in the class IV tree; plant roots and mycorrhizae grow through cracks and channels of the brown cubical rotted heartwood. Numbers of species of mycorrhizal and decomposer fungi increase, as does the potential variety of interactions among the fungi and between the fungi and higher plants. The variety of mycorrhizal fungi further increases as lichens and mosses become established on the upper surface of the fallen tree (Göbl 1968). Moss communities capture and accumulate many nutrients from rain, and these nutrients can be cycled into higher plants by the mycorrhizal fungi (Binkley and Graham 1981, Nadkarni 1981). At the same time, fungi and roots that bridge rotten wood to underlying soil may transfer soil nutrients to the fallen tree. As fungal cells or fine roots within the wood die, the minerals acquired from the soil add to the nutrient capital of the tree. These tissues can then be decomposed and their nutrients recycled into further growth of wood-inhabiting organisms.

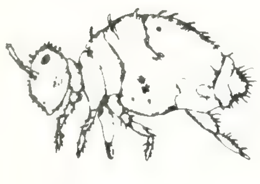
The class IV tree gradually becomes well permeated with roots as it decays into class V. The well-rotted heartwood provides a moist substrate in which mycorrhizal fungi and roots can continue to interact into the summer, well beyond the time that fungi and fine roots have become dormant or dead from drought in the upper layers of mineral soil (Harvey and others 1978, 1979a; Place 1950).

Relatively few species of mycorrhizal fungi seem able to grow in rotten wood compared with the number that grow in soil (Göbl 1968, Kropp and Trappe 1982), perhaps because most mycorrhizal fungi do not produce the enzymes needed to decompose the tannins and other phenolic compounds in wood (Giltrap 1982). Some of the mycorrhizal fungi that inhabit both mineral soil and rotten wood develop much more strongly in the wood than in the soil (Trappe 1962, 1965), and some appear to be restricted to rotten wood (Kropp and Trappe 1982). Most mycorrhizal fungi in rotten wood produce mushrooms or truffles as their spore-bearing, reproductive bodies, but they can do this only if they are in symbiotic association with host roots. This particular result of a fungus-plant interaction occurs mostly in class IV to V trees and is an important feature of the animal-plant interactions discussed in the following sections.

Animal-plant.—The introduction of fungal spores into a recently windthrown, class I tree by bark beetles and wood borers initiates a sequence of complex animal-plant interactions that continues until the tree disappears altogether. Once established and growing under the bark, the fungal colonies are grazed by a variety of invertebrates (McMillen 1976, Petersen 1971, Russell 1979). Many decomposer fungi sporulate within fallen trees and depend on insects for dispersal of spores. Thus, the young bark beetles, emerging from under the bark where they began life as eggs, take with them spores of the associated fungi. Similar relationships between insects and fungi probably occur through all decay stages of fallen trees. Insects eat the fungi and disperse the spores. Many of the fungal grazers are food for predators, so the animal-plant interactions are a prelude to animal-animal interactions.

As the fallen tree progresses through decay classes II and III, the zone of decomposition beneath the bark provides shelter to additional invertebrates and substrate for roots and mycorrhizae. The mycorrhizal fungi are thus introduced to the system as an additional food source to grazers, such as nematodes (Riffle 1971), aphids (Zak 1965), and collembolans (Warnock and others 1982). Slippage of the bark, and eventually of decayed sapwood, removes that favorable environment and the organisms within it from the top and sides of the tree; that material, however, does not disappear. Most of it accumulates loosely alongside the log to provide a new habitat favorable to many of the same organisms as before, plus larger animals, such as slugs, snails, salamanders, and small mammals.

Various mites, insects, slugs, and snails feed on the higher plants that become established on rotten wood. These plants also provide cover for the animals, as do the lichens, mosses, and liverworts that colonize fallen trees in decay class IV. Wood-boring beetles, termites, and carpenter ants produce channels in the heartwood that provide passageways for roots. The fruiting bodies of the mycorrhizal fungi, produced from energy supplied by the host plant, can also be a major source of food for insects (Fogel and Peck 1975); other arthropods (Buller 1922); and small mammals, such as the California red-backed vole (Fogel and Trappe 1978; Maser and others 1978a, 1978b; Ure and Maser 1982).



Collembolan

Specific groups of animals exemplify these generalities. Collembolans are tiny, wingless insects, most of which jump by means of a springlike appendage on the abdomen—hence, the common name "springtail." Collembolans living in the soil can be divided into two groups: (1) those that live in the surface layer and feed on fungi, algae, lichens, and decaying vegetation; and (2) those that live deeper in the soil and graze on micro-organisms (Edwards and others 1970, Furniss and Carolin 1977, Zachariae 1962). Both groups probably also exist in fallen trees. Those that feed on fungi, algae, lichens, and detritis could inhabit the protected areas in the exterior bark of a class I tree as their food supply begins to accumulate. As the tree's interior is made available, first by inner bark feeders and then by wood borers, collembolans gain a new dimension in habitats and niches. By the time a decomposing tree reaches decay class III, insect tunnels have penetrated all levels and the entire tree is "open" so collembolans can live deep within it and graze on such micro-organisms as bacteria.

Because collembolans occupy essentially any atmospheric habitat, they are extremely versatile. The greatest number and variety of species are found in the soil or in contact with it, especially where organic materials abound. Most species are susceptible to desiccation; but in damp environments, species that normally would be restricted to the soil or to litter may occur on the surface of the ground or even in standing trees (Christiansen and Bellinger 1980).

Development of collembolans is not necessarily continuous; growth is interrupted in cold seasons. Development of eggs and immature stages may also be interrupted by dry conditions. Dry periods are survived by a form of diapause, a suspension of growth or development. In a few genera, diapause is even associated with a regressive modification of the mouthparts and digestive tract, and sometimes also with striking external modifications (Christiansen and Bellinger 1980).

Collembolans molt throughout life, from 2 times to over 50 times. Growth apparently continues throughout an individual's life, but at a decreasing rate after sexual maturity. Sexual activity of adults appears to be restricted to alternate instars (Christiansen and Bellinger 1980).

As with collembolans, the mite fauna diversifies within a fallen tree over time. In fact, the mite fauna in rotten wood may be surprisingly complex. As stated by Krantz (1978, p. 57), "The remarkable diversity in morphology . . . is more than equalled by the variety of behavioral characteristics . . . . Specializations in habitat often are paralleled by specializations in structure."

Oribatid mite

Mites can be divided initially into two groups—free living and parasitic. The free-living forms exhibit a variety of food habits.

Small-plant eaters include mites that feed on bacteria, algae, fungi, and lichens. Such mites occur in the soil and the litter of the forest floor, and they can inhabit the outer bark of a class I fallen tree as it becomes suitable. As dead plant and animal materials accumulate on a fallen tree, mites (which relish putrid material) become part of the community. The strategy of feeding on dead organisms has been even further refined by the mites; some feed on the decaying material of higher plants (large-plant eaters), whereas others are considered to be general plant eaters, consuming fungi, bacteria, and algae, as well as decaying material from higher plants. The general plant eaters often depend on fungi to soften, decay, and prepare the plant tissues. As organic materials increase, an array of fungi becomes established, and mites that prefer fungi for food appear on the scene (Krantz 1978, Luxton 1972).

Mites immigrate into a fallen tree as other organisms, such as wood-boring beetles, penetrate it and modify its habitability. As a fallen tree is colonized by bacteria, fungi, and yeasts, mites that dine on these organisms also take up residence. As these organisms live and die, mites that feed on dead tissues join the community and add to its diversity. Our observations suggest that the mite fauna really begins to flourish as a fallen tree approaches class IV. Finally, as the fauna increases and diversifies, the fecal output generates still another level in the partitioning of food resources available to the mite community.

Even in death, mites and other invertebrates interact with plants. Their empty exoskeletons serve as incubators for the spores formed by certain mycorrhizal fungi (Rabitin and Rhodes 1982).

Common earwig

A larger inhabitant of fallen trees is the common earwig. The earwig is mainly nocturnal and spends the day in cracks and crevices and under the bark of large fallen trees, as well as in other places. Although reputed to feed on tender foliage and dead or decaying vegetable matter, it also devours both living and dead insects (Borror and DeLong 1964, Imms 1960, Langston and Powell 1975).

Unlike most insects, the common earwig cares for its eggs and young. After depositing a group of eggs in the soil in winter or early spring, the female rests over them much as a hen does her chicks. The newly hatched earwigs remain under and around their parent until they are able to fend for themselves. Common earwigs become adults in summer, and having wings and being capable of flight, they can disperse. There appears to be one generation per year (Imms 1960, Langston and Powell 1975).

Although some common earwigs may be primary tenants of large fallen trees, others may be secondary or part-time tenants. Nevertheless, they are an important part of the food chain, as will be seen in the next section.

The California red-backed vole is the quintessential example of interactions within fallen trees (fig. 23). The vole heavily uses them for cover; we have found that most class II through class V old-growth Douglas-fir trees have vole tunnels underneath. The vole eats mostly fungi and includes lichens but prefers truffles (Ure and Maser 1982). Some truffles, such as *Rhizopogon vinicolor,* fruit mostly in rotten wood, where their mycelium forms the tuberculate mycorrhizae of conifers (Trappe 1965, Zak 1971) (figs. 24 and 25). The truffle spores are dispersed by animals that eat the truffle (Trappe and Maser 1976). Thus, there is a tight cycle of interdependence: the vole needs the truffle for food; the truffle depends on the vole for dispersal of spores and on a mycorrhizal tree host for energy; the tree requires mycorrhizal fungi for uptake of nutrients and provides the rotten wood needed by the vole for cover. Moreover, since both voles and *Rhizopogon vinicolor* specialize in rotten wood as habitat, the vole disperses the *Rhizopogon* spores to the kind of substrate in which the fungus thrives.

Figure 23.—The California red-backed vole depends on decayed fallen trees as habitat (photo, courtesy of D. Ure).

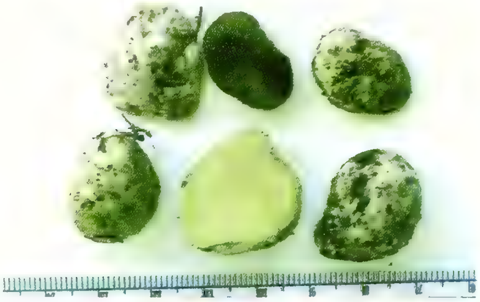
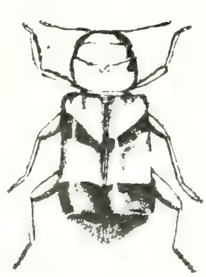


Figure 24.—Fruiting bodies of *Rhizopogon vinicolor* A. H. Smith: left and right, surface views; center, cross sections. This fungus typically forms mycorrhizae with Douglas-fir roots in rotten wood.

Figure 25.—Mycorrhizae of Douglas-fir formed with the fungus *Rhizopogon vinicolor.*

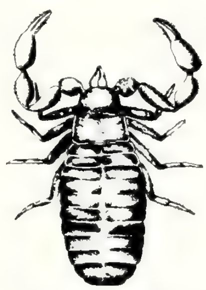


Redbellied checkered beetle

Animal-animal.—As a class I fallen tree is penetrated by the wood-boring beetles and they begin to thrive within it, Nature's system of checks and balances is also activated. At first this system is composed primarily of predaceous beetles in the families Cleridae (checkered beetles) and Trogositidae (no common name). The redbellied checkered beetle, for example, is an important predator of the bark beetle in Douglas-fir trees (Cowan and Nagel 1965). Adult redbellied checkered beetles prey on adult bark beetles, and their larvae prey on the larvae of bark beetles. There is one generation of redbellied checkered beetles annually in Oregon (Furniss and Carolin 1977).

As the diversity of fauna within a fallen tree increases, so do the number and variety of predators. Among the smallest predators are the predaceous mites. Predaceous mites are common near the surface of the soil and in mosses, humus, rotten wood, and animal waste products. They prey on small arthropods, such as collembolans, on arthropod eggs, on small roundworms, and occasionally on each other. Predaceous mites are commonly long legged and fast, and they have strong mouthparts for capturing and chewing their prey (Krantz 1978, Luxton 1972).

The next level of predation may be pseudoscorpions. These little creatures are related to spiders. They look like miniature scorpions with pinchers but without tails and stingers.



Pseudoscorpion

Pseudoscorpions move in a slow walk, but they can climb and can walk upside down on the ceilings of small caverns within rotten wood; they move backward much faster than forward. They construct silken nests in which they rest. A pseudoscorpion not occupied in spinning silk often sits in its nest with its pinchers (technically called pedipalps) and the anterior of its body protruding through the opening. From this position, it can grab a passing collembolan or mite to eat. Some species of pseudoscorpions seem to prefer small flies, small beetles and their larvae, ants, and even small earthworms (Comstock 1948, Weygoldt 1969). The pseudoscorpion keeps its nest clean, discarding prey remains as far away from its nest as possible without actually leaving the nest. An individual may leave its nest in search of food or a mate; when it cannot find its way back, it makes a new nest or occupies an empty one (Weygoldt 1969).

A female pseudoscorpion carries its eggs and developing embryos in a brood sac attached at its genital opening. The eggs are small, with little yolk, so the embryos are nourished by a nutritive fluid produced by the female. Most species reproduce in spring or summer and may have several broods per season (Weygoldt 1969).

Folding-door spider

The next order of predaceous magnitude is probably spiders, of which the Pacific folding-door spider is the largest spider inhabiting fallen trees. In general, spiders undergo little metamorphosis or change during development; when hatched, they look like miniature adults. Legs lost during development are usually regenerated. Although spider eggs hatch soon after they are laid, spiderlings that hatch in the autumn remain in the brood sac until the next spring. All spiders are predaceous; they eat mainly insects. A spider normally kills its prey by injecting poison into the captured prey with its "fangs" (Borror and DeLong 1964, Comstock 1948).

The folding-door spider's abode is a tube constructed in an existing crack within the outer layer of a class III or IV fallen tree with many cracks and crevices. The horizontal tube is completely lined with silk. To close its tube, a spider grasps the rim on opposite sides and pulls it in toward the middle. Except when capturing prey, a female seldom leaves her tube, but a male wanders in search of a mate (Levi and others 1968).

From our observations, Pacific folding-door spiders prey on whatever they can catch and subdue. Although we have occasionally found evidence of food refuse around the entrance of a spider's tube, it was usually scattered as we dissected a fallen tree and was not identifiable.

Another group of predators is the centipedes, of which *Scolopocryptops sexspinosa* (Say) (no common name) is the largest found in fallen Douglas-firs. Centipedes have one pair of legs per segment. Centipedes overwinter as adults in a protected place, such as within rotten wood. They lay their eggs in the spring and early summer. Some species have sticky eggs that a female hides with debris, but a female *S. sexspinosa* usually coils around her eggs to protect them and may periodically lick them to keep them clean (Borror and DeLong 1964, Levi and others 1968).

Centipedes are predaceous. They feed on spiders, insects, and other small animals. All centipedes have poison jaws with which they paralyze their prey. Some species, such as *S. sexspinosa,* have such stong poison jaws that they are effective even against such predators as birds and large insects (Borror and DeLong 1964, Levi and others 1968, Maser and Hooven 1974). Centipedes figure prominently as predators in trees in decay classes III, IV, and V.

As the bark becomes loose on a late class II fallen tree, lungless salamanders (family Plethodontidae) join the internal community. Three species of salamanders are associated, as predators, with rotten wood in western Oregon: Oregon slender salamander, Oregon salamander, and clouded salamander.

Oregon slender salamanders are endemic to the northern half of the Cascade Range in western Oregon (Stebbins 1966). They are most often associated with trees in decay classes III to V, either under intact bark or in termite channels deep within (Stebbins 1954). Females lay about 8 to 11 eggs in June. Large, moist, cool fallen trees are important to the Oregon slender salamander in the heat of summer because they, and other species of slender salamanders, seem to be particularly prone to fatality from heat stress (Maiorana 1977). They may actually need a suitable fallen tree for only a few weeks in summer, but without it during that time they could die.

Although we know of no specific data on the food habits of the Oregon slender salamander, a similar species that occurs in extreme southwestern Oregon and in northwestern California, the California slender salamander, will serve as an example. Both species are about the same size and inhabit forested areas. The major items in the diet of California slender salamanders are collembolans and mites, followed by such groups as flies, spiders, and small snails (Bury and Martin 1973). Evidence suggests that the California slender salamander even selects collembolans (specifically family Sminthuridae) and mites (specifically family Oribatidae) over other types of prey (Maiorana 1978). These small, slender salamanders are well suited to a role of predator within the narrow confines of wood-boring beetle and termite galleries in classes III through V fallen trees.

Another salamander, the Oregon salamander, although thought to primarily inhabit rodent burrows in forested areas (Stebbins 1954), is frequently found under pieces of bark that sloughed off large, fallen Douglas-firs. It is also found within classes III through V trees, particularly during cold or dry weather (Stebbins 1966). Individuals are usually solitary except when they are breeding or are associated with young. Egg clutches, averaging 11 or 12 eggs, are often deposited under the bark or within fallen, rotting Douglas-firs. One female with a clutch of 12 eggs was found on June 30, 1982, in a very wet class IV Douglas-fir in an old-growth Douglas-fir stand on Mary's Peak, Benton County, Oregon.

The two most important foods of the Oregon salamander are collembolans and spiders, followed by isopods (sowbugs), millipedes, and adult beetles (Bury and Martin 1973).

The third salamander is the clouded salamander (fig. 19). It frequents rotten wood, particularly Douglas-fir in late classes II through IV (Stebbins 1966). These salamanders are often found under the loose bark of large fallen trees in spaces excavated by wood-eating insects (Fitch 1936). In fact, young clouded salamanders show a striking affinity for bark (McKenzie and Storm 1970). According to Stebbins (1954), they are especially abundant in well-illuminated openings in a forest. In addition, the clouded salamander is the most arboreal member of the genus and has been found 20 feet (6.1 m) up in standing trees (Stebbins 1954).

Eggs laid in late spring or early summer under bark and in cavities in rotten wood are guarded by the female. The eggs may be attached separately by their stalks but close together, or they may have their stalks twisted around one another and be attached to a common point on the ceiling or wall of the nesting chamber (Stebbins 1954).


Isopod or sowbug


Snout beetle

Bury and Martin (1973) and Storm and Aller (1947) listed ants as the most important food of clouded salamanders. We also found ants to be an important food item, but only in summer.[2] The major food of the adult clouded salamanders in winter, spring, and fall were isopods and beetles, particularly snout beetles. Isopods, ants, beetles, and common earwigs were important in summer, when foods were eaten in greater diversity. Important foods for small juvenile salamanders (as large as three-fourths inch (19 mm) in snout-vent length) were mites, collembolans, flies, and very small beetles. Larger juveniles (more than three-fourths inch (20 mm) in snout-vent length) consumed, in order of importance, flies, isopods, beetles, mites, and centipedes in winter; beetles, ants, and isopods in spring; ants and beetles in summer; and isopods, beetles, and ants in fall (see footnote 2). Storm and Aller (1947) also found termites, probably the Pacific dampwood termite, in the stomachs of some individuals, which indicated that the salamanders had been feeding within a class III to class IV fallen tree.

The final level of predation within large, rotten, fallen Douglas-firs in classes III through V is probably that of small mammals, such as shrews and shrew-moles.

Shrews are small, with short legs, tiny eyes, and long, pointed noses. Although they cannot see well, their senses of touch, smell, and hearing are acute. The common shrew in western Oregon Douglas-fir forests is the Trowbridge shrew. This small, "nervous" mammal is abundant around fallen trees, particularly classes III and IV, that are well settled on the forest floor and have been in place long enough to act as the shrew's grocery. The Trowbridge shrew has the most catholic diet of all western Oregon shrews. It eats at least 47 types of food, the most important of which are centipedes, spiders, internal organs of invertebrates (probably mostly beetles), slugs, and snails. In addition, it shows a definite affinity for fallen trees, as do some of its prey (Maser and others 1981, Terry 1981, Whitaker and Maser 1976).

The American shrew-mole is a tiny mole. As are other moles' ears, the shrew-mole's ears are merely holes near the shoulders and are not visible because of the dense fur. It has minute eyes nearly concealed by fur, and broad front feet with stout claws adapted for digging (Maser and others 1981).

These small moles spend much time burrowing in the surface soil-litter layer and along and under classes II and III fallen trees. When trees reach classes IV and V, shrew-moles also burrow within them. Their close tie with fallen trees in old-growth forests is probably reflected in their diet (Maser and others 1981, Terry 1981); for example, in a study by Whitaker and others (1979), the three foods eaten with the highest frequency were earthworms (81.8 percent), centipedes (54.5 percent), and flies (36.4 percent).

The shrew-mole is ideally equipped to forage in and around fallen trees because its nose is extremely sensitive to touch; it is much like a blindman's cane. In almost constant motion, it quickly identifies any object it contacts. Further, this mole's small size, adaptions for digging, and herculean strength make it an efficient, burrowing predator within and beneath rotten wood (Maser and others 1981).

[2] J. O. Whitaker, Jr., and C. Maser. Unpublished data on file at Indiana State University, Department of Life Sciences, Terre Haute, Indiana 47809

Nutrient-plant-animal-nutrient.—A tree begins life with nutrients from the soil and ends life with nutrients that diffuse into the forest floor and become parts of other trees. It is appropriate, therefore, to select an element (nitrogen) that is necessary for the growth and reproduction of all organisms within a forest and to use it to represent full cycle the minisystems within a fallen tree.

As a tree grows, nitrogen is incorporated into the wood-cell structure. After it dies, processes of decomposition begin to break down the structure of the wood and ultimately to recycle the nitrogen.

During decomposition, micro-organisms (such as fungi and bacteria) incorporate nitrogen from the wood into their own cellular structures as they digest the carbon from the wood substrates. As the microbes decompose wood, the carbon-to-nitrogen ratio gradually shifts until nitrogen becomes relatively more available for plant uptake. As microbial colonization and decay increase, animals varying in size from small mites and collembolans to large beetle larvae feed on microbial tissues enriched in nitrogen from digestion of wood; and vertebrates, from California red-backed voles to black-tailed deer, may obtain some of their protein nitrogen from decaying trees by feeding on fungal fruiting bodies, such as truffles and mushrooms (Fogel and Trappe 1978, Maser and others 1978a, Trappe and Maser 1978).

As decomposition proceeds in a fallen tree, other sources of nitrogen are added in the form of leaf litter and other litter components that fall on the surface of the tree. As these decay, their nitrogen becomes available to enrich the wood; and as rainwater—rich in nutrients from passing through the tree canopy and surface litter—accumulates on the fallen tree's upper surface, some nitrogen is leached into the wood.

Microbes that colonize a fallen tree from the ground surface provide additional nitrogen, as do animals that take up residence in the tree or eliminate their metabolic waste products on its upper surface. As decay proceeds, plant roots penetrate the fallen tree's surface and tap the rotting wood as a source of available nitrogen, other nutrients, and water.

A fallen tree disappears gradually through the decades, and its nitrogen capital is returned to the forest. Weathering processes, such as freezing and thawing, and animal activities contribute to the disintegration and disappearance of the tree. Some residue may remain for centuries in the forest as it slowly becomes incorporated into the organic portion of the soil (fig. 20).

Biotic Succession Within and Around Fallen Trees

As a fallen tree decomposes, it creates a gradually changing myriad of internal and external habitats (Maser and others 1979). Plant and animal communities within a fallen tree are very different from those outside, but both progress through a series of orderly changes. As a fallen tree decomposes, its internal structure becomes simpler, whereas the structure of the plant community surrounding the fallen tree becomes more complex (figs. 26 and 27).

Figure 26.—Plant and animal communities are very different inside this class III Douglas-fir than they are outside.

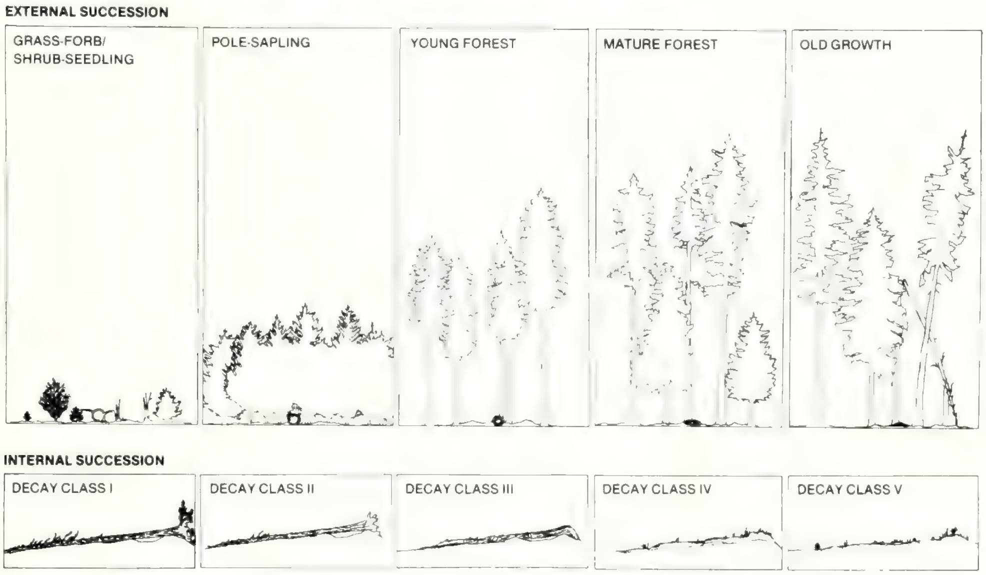


Figure 27.—Fallen trees progress through two simultaneous successional processes—internal and external (modified from Maser and others 1979).

Internal succession in a fallen tree is related to the following factors: (1) the tree species and its inherent decay-resistant chemical properties; (2) its size—the larger it is, the longer it lasts; (3) what killed the tree; (4) whether it originated as a tree or a snag; (5) the microclimate around it; (6) its placement on the ground; and (7) the biotic community peculiar to it.

Internal succession is also influenced by temperature, moisture, and stage of decay. A class I fallen tree, for example, has many readily available nutrients that support opportunistic colonizers. As decay proceeds, its moisture-holding capacity increases, but nutrients become less available because either they have been used or they remain locked in the more decay-resistant compounds of the wood. Ultimately, the rapidly growing opportunists are succeeded by organisms with more sophisticated enzyme systems, and decay continues.

External succession is related to the changes that take place in the plant community surrounding a fallen tree. A fallen tree is a connector between the successional stages of a community; it provides continuity of habitat from the previous forest through subsequent successional stages. A large fallen tree therefore provides a physical link—a nutrient savings account—through time and across successional stages. Because of its persistence, a fallen tree provides a long-term, stable structure on which some animal (both invertebrate and vertebrate) populations appear to depend for survival.

External succession is influenced by the same factors as internal succession, with the additional influence of light. Consider, for instance, a class IV or V tree that supports a lush community of mosses, liverworts, hemlocks, and other flowering plants. As the canopy closes over the opening created by the original falling of the tree, light becomes limiting to the growth of green plants. If, at this point, a nearby tree falls, the environment can change immediately and strikingly. Greater solar radiation increases the amount of light but may also raise the daytime temperature of the fallen tree. In turn, nighttime temperature may be lower because of the increased heat that reradiates to the atmosphere. In addition, more rain and snow reach the ground.

Stream Characteristics and Fallen Trees

Fallen trees and other large pieces of wood significantly shape the energy flow, nutrient dynamics, and structure of biota in streams of the Douglas-fir region (fig. 28). Streams in old-growth forests contain large quantities of organic debris: 220 to 770 tons per acre (200 to 700 t/ha). Large, organic debris shapes a stream channel by damming it, which creates ponds that trap sediments, or by obstructing it, which redirects waterflow that creates meanders and pools (Anderson and others 1978, Franklin and others 1981, Naiman and Sedell 1979, Sedell and others 1982b, Swanson and others 1976, Triska and Cromack 1980, Triska and others 1982).

Large pieces of wood in streams provide a diversity of spawning and rearing habitats for salmonids. In the smallest (first order) streams, for example, over 50 percent of the habitat is related to presence of large wood (fig. 29), and about 25 percent is created and maintained by wood in larger (third order) streams (Anderson and Sedell 1979, Franklin and others 1981, Swanson and Lienkaemper 1978, Triska and others 1982).

Most large wood is randomly spaced in small streams (first and second order) because flow volume is insufficient to transport large trees downstream. Intermediate streams (third to fifth order) have less wood. Big chunks typically accumulate where the channel is obstructed by immobile dead trees or channel constrictions; such obstructions provide sites for collection of small to intermediate size debris that moves downstream at high flows. Most debris comes to rest on the flood plains or on the outsides of bends of larger streams or rivers (sixth to eighth order). But even in big rivers, historical records show that large pieces of wood contribute significantly to in-channel structures that trap sediment, pond water, and create side channels and sloughs (Franklin and others 1981, Naiman and Sedell 1979, Sedell and Luchessa 1982, Swanson and others 1976, Swanson and Lienkaemper 1978).

The food base or energy supply of a stream in an old-growth Douglas-fir forest is primarily litter from the adjacent forest combined with algae produced in reaches of streams exposed to light. Pristine streams retain much of the forest litter. Fallen trees in a stream form "stairsteps" that allow over 70 percent of the litter to be retained long enough to be biologically processed by stream organisms. Similar relationships exist for pristine streams in the Canadian boreal forest (Naiman 1982, Sedell and others 1975, Triska and others 1982).

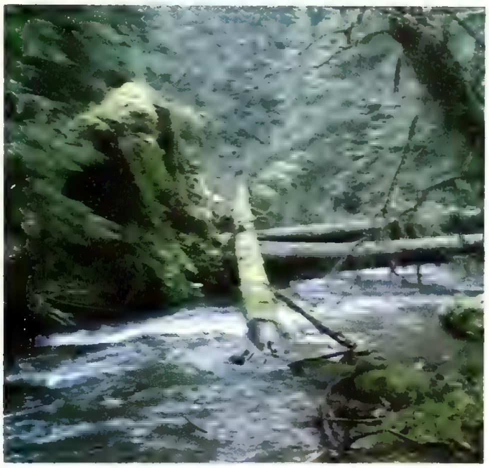


Figure 28.—Note how the fallen tree (foreground) channels the water against the rootwad (left) that, in turn, buffers the streambank from the current.

Figure 29.—The stable, fallen tree forms an obstruction that dissipates some of the stream's energy and creates a pool used by salmonids.

The influence of the forest as a source of energy and as a channel structure diminishes as a stream gets larger. Edges of an unmanaged stream, however, are dominated by forest vegetation, and fallen trees create and maintain side channels and small backwater areas that are prime sites for deposition of organic materials and rearing of coho salmon (Sedell and others 1982a). Further, old-growth forests typically have a mix of herbaceous and shrubby plants and areas of various sizes exposed to sunlight; this combination provides a stream with a mix of coniferous and deciduous leaf litter as well as patches of algae. Such diversity of habitat and energy provides an interactive aquatic system with a stable, rich mix of both invertebrate and vertebrate species.

A Historical Sketch of Woody Debris in Northwest Waterways

Most early descriptions of Northwest streams and rivers are recorded in British and United States army journals. They tell, for example, of valleys so wet that early travel was along the edges of the hills and not along the valley bottoms (Dicken and Dicken 1979). The Tualatin Valley was described in British army journals as "mostly water connected by swamps" (Ogden 1961, p. 122). Much of this flooding was a result of beaver activity and accumulated sediment, fallen trees, and living vegetation in the channels. Because the valley bottoms had accumulated fine silt and organic material of alluvial origin, the land was fertile, and the task of draining it for farming began early in Oregon and Washington.

Oregon State Agricultural College soils scientist, I. A. Williams (1914, p. 13), wrote of the condition of Willamette Valley streams in 1910:

> Many of the smaller streams. . . through these flat sections of the valley flow sluggishly and frequently overflow their banks during periods of heavy winter rainfall. . . . Most of these have sufficient grade to carry even more water than ordinarily comes to them; seldom less than 3, and usually more, feet of fall per mile. The annual overflow is caused from the obstructing of the channel by the growth of trees and the extension of their roots, the dams thrown across the channels by beavers and the consequent accumulation of sediment and other debris, etc. . . . It is a common condition, however, and usually all that is necessary is a clearing out and opening up of the clogged channel of the stream to afford entire relief . . . to the farmer . . . .

Descriptions of streams in the Puget Sound lowland and the Willamette Valley were similar. Most consisted of a network of sloughs, islands, beaver ponds, and driftwood dams with no main channel. The Skagit River lowlands encompass about 198 square miles (512 km^2), of which over 50 square miles (128 km^2) were marsh, sloughs, and wet grass meadows. U.S. Army Corps of Engineer maps for 1875-91 for the lower Nooksack and Snohomish Rivers in Washington show large areas of sloughs, swamps, and grass marshes (Reports of the Secretary of War 1875-99). All the coastal Oregon valleys contained marshy areas and numerous sloughs. The interaction of the streams and their flood plains in the lowlands of both States was great before they were cleared and channeled by pioneer farmers (U.S. Congress, House 1848).

The channels of fast, turbulent rivers and low-gradient rivers, regardless of alluvial or bedrock control, were influenced by large amounts of wood. The lower Siuslaw River and lower North Fork Siuslaw River were so filled with fallen trees that trappers were unable to explore much of these river systems in 1826 (Ogden 1961). The Willamette River flowed in five separate channels between Corvallis and Eugene in 1870.

Reports of the Secretary of War (1875-99) state that the "obstacles were . . . great above Corvallis" and the riverbanks were heavily timbered for half a mile (0.8 km) on either side. Over 5,500 drifted, dead trees were pulled from a 50-mile (80-km) stretch of river in a 10-year period. The trees ranged from 5 to 9 feet (1.5 to 2.8 m) in diameter and from 90 to 120 feet (27.7 to 37 m) in length. The river was also confined to one channel by engineering activities. In both Oregon and Washington, other rivers were completely blocked by driftwood in the lower, main channels. The Skagit River, for example, had a driftwood jam that was three-fourths of a mile (1.2 km) long and one-fourth of a mile (0.4 km) wide. The Stillaguamish River was closed by six driftwood jams from the head of tidewater to river mile 17 (km 27.2). Drifted, dead trees were so numerous, large, and deeply imbedded in the bottom that a steam "snag boat" had to operate for 6 months to open a channel 100 feet (30 m) wide.

Driftwood jams in high-gradient river systems were often located where the channel gradient abruptly decreased. Morse (1883, p. 9) described the South Fork Nooksack River:

> . . . we came to a place where the river, during freshets had ground sluiced all the earth away from the roots of the trees, and down some 6 feet to the gravel. This covered a region of country a mile in width by five in length. Overgrown yellow fir timber had once covered most of that section. If the river below there was only clear of jams that place would be a paradise of hand loggers. On the gravel lay many million feet of sound fir timber, which only needed to be junked up during the summer and the winter freshets would float the logs down to the sea. Immediately below this place, the jams first extend clear across the river, and for the next 20 miles there is a jam across the river nearly every mile.

From the above scenario, it is obvious that large, woody debris was an important factor in the early river systems of the Pacific Northwest (figs. 30 and 31). Human objectives, other than watershed management, however, dictated clearing the rivers; so present practices downplay the ecological role of large, woody debris in modern river systems.

Figure 30.—Logs in a small stream awaiting enough water to be floated to the mill (photo from USDA Forest Service historical files).

Figure 31.—A splash dam at Austin Place, Hamilton Creek, Oregon, August 16, 1907. Such dams were used to regulate the flow of water to float logs down a stream to the mill. (Historical photo, courtesy of the Horner Museum, Oregon State University.)

Figure 32.—Note the large pieces of wood on the flood plain, especially in the lower right corner where the stable wood has formed a protected site that has allowed the alder to grow.

Vegetation of Streamsides and Gravel Bars

Large, fallen trees have both positive and negative effects on live vegetation that borders watercourses. Trees carried by floodwaters can severely batter live plants on a flood plain, but this is normally restricted to a narrow belt along the immediate channel. Stabilized, large pieces of wood, on the other hand, provide protected sites where alder and other species of plants can become established (fig. 32).

Once established, live vegetation begins to stabilize a stream channel. Such features as a gravel bar also become stabilized and enriched with fine sediments and organic materials as plant root systems develop and the stems resist the flow of water and reduce its velocity.

Fallen trees protect thickets of vegetation on exposed channel bars. Alders growing in bordering areas not protected by down trees sustain heavy, repeated pruning by floating woody debris and moving bedloads (Swanson and Lienkaemper 1982). The down trees that protect the outer edge of a thicket and those in the thicket itself create local environments of quiet water where fine sediments and organic debris are deposited during high flows. This process, coupled with the production of leaf and woody litter by the stand, results in soil development and growth of the stand. The large, down trees thus help a stand to reach the stage of structural development that allows it to better withstand floods.

Fallen trees on gravel bars also provide sites where some stream-transported species of hardwoods and shrubs can reroot and grow.

Restabilization of streams after major floods, debris torrents, or massive landslides is accelerated by the presence of large, woody debris along and within a channel. Swanson and Lienkaemper (1978) found that after a fire an aquatic habitat was maintained by the large, woody debris (supplied to the stream by the prefire forest) while the postfire forest was developing. In many instances, however, salvage logging of streamsides destabilizes the structure of the channel and thereby the quality of the habitat.

Decomposition and Nutrients in Streams

Small streams that drain heavily forested watersheds depend on organic materials from the adjacent forest as a source of carbon and nutrients for biological processes. Energy flow and nutrient cycling are measured by calculating the budgets of carbon and nitrogen in a stream. By examining the internal transfer of organic materials and nutrients, we can gain significant insights on the ability of a small stream to process incoming sources of energy. Sedell and others (1974) and Triska and others (1982) studied a small stream in the western Cascade Range of Oregon. They found that 85 percent of the organic material in the stream was large, fallen trees or branches from large trees. Of the tree leaves and needles that fell into the stream during the year, only 10 to 20 percent were transported downstream. The remainder were either stored in the channel or used as food by microbes. Microbial respiration accounted for about 55 percent of the carbon produced. There also was a large amount of fine detritus that was partly formed as a byproduct of the decomposition of large pieces of wood.

Large wood was the primary structural feature of small streams, and it dominated the carbon budget. The structural characteristics of large wood allowed leaves and needles to be retained in a stream long enough to be used as food by microbes and invertebrates. Without the wood, such material would be rapidly transported downstream, and the stream system would not be as efficient in processing organic material. The ability of a small stream to process organic material is also important because the stream provides preconditioned food to biotic communities in larger streams and rivers.

Retention of organic material is important to a stream ecosystem in that large quantities of stored organic material buffer the annual fluctuations in energy flow. During periods of drought, for example, enough moisture and waterlogged material remain available in a stream to provide habitat and food for aquatic organisms; during major floods when large amounts of organic material are transported downstream or washed up on the banks, enough remains to continue to provide habitat and food for aquatic organisms.

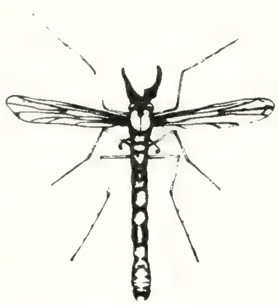
It is important to understand that carbon, nitrogen, and all the other materials that leave a watershed either pass through or accumulate in the stream environment, which encompasses less than 1 percent of the watershed area. Such a concentration of nutrients, the capacity of a stream to store organic material, and the efficiency to process it depend on the number and quality of fallen trees in the stream.

Figure 33.—Some of these fallen trees will become waterlogged; others will be submerged only during high water. Both circumstances affect the rate of decomposition.

Decomposition and nutrient cycling.—Trees that fall into streams decompose at different rates and in different patterns than those that fall on the ground. Decomposition in water is slower than on land because waterlogging prevents deep diffusion of oxygen into the wood; the fungi and invertebrates that cause the most rapid decomposition of fallen trees on land are strongly aerobic (Triska and Cromack 1980). Waterlogged parts of fallen trees tend to decompose in thin surface layers, about one-fourth inch (0.5 cm) thick. As the decomposed surface is grazed or abraded, oxygen can penetrate farther into the underlying wood, which in turn becomes substrate for the decomposers. If only part of a fallen tree is in constant contact with water, that part decomposes slowly but the exposed part may decompose quite rapidly because neither a low level of oxygen nor extremely high or low moisture content limits decomposer activity. Trees that fall in very small streams may contact water only during the rainy season when the stream is flowing at its highest, and lack of moisture the rest of the year may slow their decomposition (fig. 33).

As decomposition of large pieces of wood advances, the concentration of essential nutrients, such as nitrogen and phosphorous, increases. Nitrogen increases primarily through biotic use of the carbon and through fixation of nitrogen. Nitrogen-fixing micro-organisms use both the wood and the bark of a fallen tree. Although bark decays more slowly than wood, the tannins in Douglas-fir bark are not effective in reducing nitrogen fixation (Baker and others 1983). Nitrogen fixation on fallen trees in streams accounts for 5 to 10 percent of the annual nitrogen supply to the stream (Triska and others 1982).

Aquatic Invertebrates



Midge adult

The continuum of animal associations on woody debris in aquatic systems varies from being restricted to the wood to using it opportunistically. The sequence of colonists parallels the stage of wood decay. New wood entering a stream is used primarily as habitat, although some species of midges (Chironomidae) tunnel in the cambium and phloem. The wood is then colonized by a community of algae and microbes that provides food for a group of insects, functionally called grazers or collectors. Although this type of feeding does not significantly affect the structure of the wood, the colonization of the superficial layer of the wood by fungi softens it enough that it may be abraded and ingested by invertebrates that scrape their food off surfaces. Most important, however, the wood becomes suitable for obligate wood grazers and the more generalized wood shredders, such as caddisflies (Trichoptera) and stoneflies (Plecoptera), that ingest the wood infested by fungi. These activities result in a more sculptured surface texture that in turn provides habitat for many organisms. Decades of fungal colonization and growth soften the wood and allow oxygen to penetrate. Invertebrates that bore into the internal matrix of a fallen tree speed the decomposition process by consuming the wood and by transporting microbes into the tree. In the final phase of decay, detritivores—such as annelid worms (earthworms)—penetrate the material; continued decomposition then resembles that in soil and damp, terrestrial habitats (Anderson and others 1978, Dudley and Anderson 1982).

In contrast to sound wood that enters a small stream as described above, some wood is already conditioned by fungi and other terrestrial organisms before it enters the water. Such preconditioning shortens the aquatic decomposition process by allowing more rapid internal colonization by aquatic microbes and invertebrates. Decomposition is also faster in larger streams during periods of high water because the physical abrasion removes softened tissue as the wood is transported downstream or deposited on a flood plain or the outside of a bend in the stream. Only in small headwater streams or in backwaters of larger streams can rotting wood retain enough structural integrity to provide a substrate for aquatic invertebrates during the final stages of decomposition.

Dragonfly adult

Invertebrate use of wood substrates.—Quality and texture of wood are important in determining the kinds of organisms that will colonize it. The species of wood, degree to which it is waterlogged, and decay class all affect the quality. The extent of colonization by terrestrial fungi and wood-boring insects also influences the attractiveness of the wood once it enters the water because such activity is closely associated with decay class. Dudley and Anderson (1982) found that about two-thirds of the obligate wood-using organisms were generally in soft wood; one-third in grooved, textured wood; and less than 10 percent in solid, smooth wood. In contrast, the facultative organisms occurred as follows: 20 percent on solid, smooth wood; 60 percent on grooved wood; and 20 percent on or in soft wood.

Aquatic invertebrates are also functionally classified by how they use wood substrates: (1) boring or tunneling; (2) ingesting of wood by grazing, scraping, or rasping; (3) scraping algal communities growing on wood; (4) attaching to the wood or hiding in its grooves; and (5) preying. Classification based on function are interrelated with the texture of the wood, which partly explains why a higher incidence of facultative organisms are associated with smooth, firm wood and obligate organisms with soft wood. Smooth wood surfaces are suitable for attachment and for grazing the microbial film, whereas soft wood is more easily penetrated by borers and contains fungal mycelia as a source of nutrients (Anderson and others 1978).

Cranefly adult

Many of the surface-associated invertebrates are more opportunistic in their selections of feeding sites and habitat than are the internal associates. Invertebrates that use the surface probably do so for protection from the stream current, suspended sediments, and predation but not for obtaining food. The many grooves, crevices, and loose pieces of bark on a well-conditioned fallen tree held the majority of invertebrates collected by Dudley and Anderson (1982).

Borers include some families of semiterrestrial or semiaquatic beetles (Coleoptera) and some caddisflies that hollow out twigs for cases in which they live and others that tunnel into soft wood to pupate. Fly (Diptera) larvae, however, are among the dominant borers, both in abundance and species richness. The depth to which a species (insect or microbe) can penetrate the wood is probably restricted by oxygen gradients that account for the fact that galleries are located just under the surface of the wood.

Boring activity exposes new surfaces of sound wood to microbial inoculum and colonization. When such activity is associated with some of the obligate species of fly larvae, a visible zone of stained wood often radiates outward from the larval galleries; the staining is caused by fungi that may be symbionts carried by the fly larvae. Existing galleries of terrestrial beetles increase fungal activity after the wood is submerged in water, and they are also prime habitat for cranefly (Tipulidae) larvae.

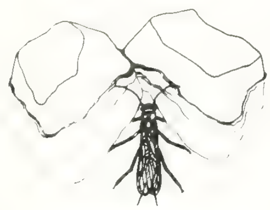
In essence, feeding activities of borers, grazers, scrapers, and raspers result in continual utilization and decomposition of wood. The amount of wood ingested depends not only on the method of feeding and the rate of consumption but also on the firmness of the wood and the amount of fungal penetration into its superficial layer. Firm but grooved or textured wood generally has a soft, stained layer one-eighth to three-sixteenths inch (2 to 5 mm) deep that has been colonized by fungal mycelia. Grazers and shredders (beetles, caddisflies, and some stoneflies) exploit this area enriched by fungi, which contains about five times as much nitrogen as occurs in nonenriched wood.[3] Scrapers (mayflies, Ephemeroptera) and raspers (snails, Mollusca) also ingest the soft layer and the periphyton—an assemblage of minute organisms attached to surfaces submerged in water.

Mayfly adult

Many species associated with thoroughly decomposed wood are detritus feeders that just happen to be in the wood instead of in some other soft, organic material, such as leaves. The feeding and burrowing activities of the detritivores reduce the size of particles and cause mineralization of the woody material.

Net-spinning caddisflies frequently use textured, wood surfaces to attach their nets and to conceal themselves. Fallen trees also direct streamflow in a manner that provides net-spinning caddisfly larvae with ideal sites, both of surface structure and water velocity, for attaching their nets and filtering food from the water. In one study, for example, Dudley and Anderson (1982) found densities of 120 caddisfly (*Hydropsyche* sp.—no common name) larval nets per 12 square inches (100 cm^2) of wood.

[3] K. Cromack, Jr. Unpublished data on file at Oregon State University, Department of Forest Science, Corvallis, Oregon 97331.



Stonefly adult

Another use of wood in streams is for pupation. Many caddisfly larvae pupate on or in wood; and several families of flies, especially crane flies, bore into soft, saturated wood to pupate. In addition, many species of insects use partially submerged wood to crawl out of the water so they can emerge as terrestrial adults. Stoneflies and some species of mayflies and dragonflies exemplify taxa that seem to prefer wood to mineral substrates for emergence as terrestrial adults.

Fish Habitat

The important role of large, woody debris in creating and maintaining spawning and rearing habitat for fish has been recognized and documented within the last 10 years (Swanson and Lienkaemper 1978, Swanson and others 1976). But we are only now beginning to really appreciate the seasonal differences in function provided to salmonids by woody debris.

Summer.—Several streams were examined in western Washington so that the population biomass of salmonids in streams flowing through old-growth forests could be compared with that in recently clearcut areas (Bisson and Sedell, in press). Although the total salmonid biomass increased in a clearcut, the species richness declined to a population of steelhead trout, the majority less than 1 year old. Coho salmon and cutthroat trout, between 1 and 3 years old, were proportionately less abundant in the clearcuts. Bisson and Sedell (in press) related the shifts in composition of species and age groups to changes in the habitat caused by the cutting of old-growth trees and by the removal of large, stable, woody debris from the stream channel. The amount of stable debris declined and the amount of unstable debris increased after passage of the 1976 Washington Forest Practices Act that mandated immediate removal of debris after logging. Pool size appeared to decrease and riffle size to increase as a result of clearcutting and channel clearing. The frequency (number per kilometer or mile) of both pools and riffles appeared to decline in clearcuts, which suggested that the normal stairstep stream profiles had been altered to a more even gradient.

Pools and backwaters are used by coho salmon and large cutthroat trout; in fact, pool volume is directly related to coho biomass in coastal streams in Oregon. In addition, large, stable, woody debris is preferred as protective cover by young coho salmon, yearling steelhead, and older cutthroat trout, particularly in high-gradient river systems (Bustard and Narver 1975a, 1975b; Everest and Meehan 1981; June 1981; Lister and Genoe 1979; Nickelson and others 1979; Osborn 1981; Sedell and others 1982a, 1982b) (fig. 34).

Winter.—Most species of salmonids exhibit shifts in preference between summer and winter habitat. Large, stable, woody debris is important to the selection of winter habitat by coho salmon, steelhead trout, and cutthroat trout. The presence of large, woody debris enhances the use of different habitats within pools. Pools are preferred by all species at base streamflows during the winter. The level of preference, however, is determined by the quality of the pool and the abundance of woody debris; the more woody debris, the greater the use of the pool. Further, large, stable debris tends to attract fish more to pools along the edge of a stream than to pools in the middle of a channel.

Figure 34.—Large, stable, woody debris increases the habitat value of a pool for salmonids.

Figure 35.—Salmonids use the stable wood on the flood plain as protective cover during winter floods.

When winter storms cause streams to flood, the pool-riffle sequences or stairstep stream profile is transformed into a continuous, high-velocity torrent, and there is little protection for salmonids from moving bedload sediment or swift, turbulent waters. During these unpredictable but brief periods, slack water refuges are associated almost exclusively with such large, woody debris as fallen trees and with standing vegetation in riparian flood plains (fig. 35). All three species of salmonids enter these debris-enhanced refuges until streamflows subside. Large, woody debris may also expand the feeding space by creating or enhancing the amount of slow-moving or standing water in organic-rich flood plains, even along the smallest streams (Bustard and Narver 1975a, 1975b).

Management Impacts on Fallen Trees

The Douglas-fir forests of the Pacific Northwest evolved with a continuing deposition of fallen trees to the forest floor and to streams. Fallen trees may periodically have been partially destroyed by fire but were ultimately replaced during development of successive stands (Harris and others 1982, Swanson and Lienkaemper 1978).

What will happen to the Douglas-fir ecosystem when fallen trees are no longer added, as will be the case under intensive forest management with increased utilization of wood fiber? And what will happen under short rotation management, when large trees are no longer produced?

These questions—and others that we do not yet know to ask—can be answered only through careful research. Until such research has been done, we only speculate. Our speculation in turn can be based only on what we know about the functions of fallen trees. These functions relate to the size, shape, placement, porosity, and cohesiveness of a fallen tree; its suite of functions is altered when any one of these factors is changed (Fellin 1980). We can thus begin to consider how stand management will affect each function.

On Land

Trees in an unmanaged forest generally fall randomly, although a storm or catastrophic event, such as the explosion of Mount St. Helens, sometimes causes all the trees to fall in one direction over a substantial area. Diversity results from the common random placement; some fallen trees lie along a slope, others across it. Trees that fell two centuries ago are mixed with those that fell two decades ago, 2 years ago, and 2 days ago. Some fell on the ground, some across others; some are whole, some broken. The resultant diversity provides a myriad of habitats in both time and space.

Machine entry in a stand reduces diversity because heavy equipment fragments and scatters class IV and V rotten wood. Class I and II trees may be salvaged or cut for firewood; class III trees that hang together and are not removed as salvage or firewood tend to become bunched or aligned along the direction of skidding. Habitat diversity declines to a fraction of what had been available (Eckholm 1975); probably fewer kinds of organisms can thrive. Further, because woody substrates serve as long-term soil organic material and nutrient reservoirs, increasingly intensive timber management, coupled with shorter rotations, could significantly alter the role of decaying wood in the nutrient cycling processes.

A forest manager can take steps to maintain the present diversity of fallen trees on a site. Machine trails can be designed to minimize the scattering of class IV and V trees. Wood utilization standards can be adjusted to leave a good representation of younger classes. Some trees—both defective and sound trees for built-in diversity—can be left to become fallen trees of the future. Where necessary, burning of slash can be designed and timed to minimize destruction of woody residue. These are all feasible practices, but they will cost money. Hence, the forest manager needs to know how a stand will benefit from the fallen trees over the long run.

In Streams

When fallen trees and other large pieces of wood are removed from stream channels and riparian zones by massive debris torrents or excessive postlogging channel cleanup, carrying capacity for salmonids in winter is reduced (Bisson and Sedell, in press; Swanson and Lienkaemper 1978; Toews and Moore 1982). In turn, the smolt yield of anadromous salmonids is reduced the next spring. Sedell and others (1982b) examined the long-term history of debris management. They concluded that the systematic removal of fallen trees and debris jams for navigation and transportation of logs in the late 19th and early 20th centuries destroyed a major structural component of fish habitat in intermediate to large rivers.

Enhancement or mitigation efforts designed to improve fish passage by removing debris jams and logging slash have resulted in declines in wintering populations of salmonids in small streams[4] (Bryant 1982, Lestelle 1978). The decline in the summer rearing capacity of a stream for coho salmon is a direct result of less large wood that provides cover and forms pools in streams (Bisson and Sedell, in press).

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[4] Elliott, S. T. Ecology of rearing fish. Annual performance report, study OIB. Alaska Department of Fish and Game; 1979; 19: 39-52.

Hall, James D.; Baker, Calvin O. Biological impacts of organic debris in Pacific Northwest streams: Proceedings of workshop 1; 1975 September; Corvallis, OR. Oregon State University; 13 p.

Research Needs

Recent and current research in old-growth forest is revealing much about the roles and qualities of fallen trees. Understanding this information may allow use of fallen trees as sensitive barometers of the "habitat health" of a stand (Harris and others 1982). To learn how the functions of fallen trees differ in an old-growth stand, a clearcut, and a young stand, we need to compare the characteristics and inhabitants of fallen trees in such areas. The physical qualities of a fallen tree—moisture, temperature, nutrient content, pH—are likely to change markedly with stand removal, regeneration, and regrowth. We need to learn how the plants and animals change with such alterations within and around a fallen tree. We especially need to know much more about the fallen tree-soil interface, probably the single most important habitat niche for the survival of organisms in drastically altered stands. To fully interpret the long-term significance of fallen trees and the old-growth forests from which they come, we need to learn more about their contribution to the forest ecosystem as a whole and to the quality of the soil in particular.

Research on fallen trees in streams needs to address the quality and quantity of the woody debris that is required in riparian zones to maintain or enhance the aquatic ecosystem. Because saturated wood decomposes slowly, it accumulates on the bottom of a stream to become a site of nitrogen fixation and nitrogen, to form habitat, and to help capture and hold leaf litter that in turn is a source of energy for the stream ecosystem. How many live trees are needed (and of what diameter) to provide a future source of fallen trees in a stream for structure, nutrient cycling, and fish habitat? Although most fisheries biologists have focused their attention on wood in streams, of equal importance is the large wood (quality and quantity) along channel margins and in overflow areas because this is the winter habitat of the salmonids.

In summation, we must not sacrifice the options of future generations on the altar of cost-effectiveness through decisions based on insufficient data. It is the professional charge of researchers to obtain the needed data and of managers to apply it.

Epilog

> When thinking of and dealing with diversity in a forest, conventional vision focuses on structure and habitat. Diversity, however, has another dimension—one that is only now being perceived: function. The basic components of structural and functional diversity are inseparably interwoven in a forest. A broadened philosophical view of management—a forest versus a commodity—is necessary if certain structurally related functions, such as retention of water and cycling of nutrients in large, fallen trees, are to be options in managed forests of the future.
>
> (Maser and Trappe 1984)

Common and Scientific Names

Plants:

Alder	*Alnus* spp.
Douglas-fir	*Pseudotsuga menziesii* (Mirb.) Franco
Huckleberry	*Vaccinium* spp.
Oregon oxalis	*Oxalis oregana* Nutt. ex T. and G.
Salal	*Gaultheria shallon* Pursh
Sitka spruce	*Picea sitchensis* (Bong.) Carr.
Western hemlock	*Tsuga heterophylla* (Raf.) Sarg.

Invertebrates:

Carpenter ant	*Camponotus* spp.
Common earwig	*Forficula auricularia* L.
Douglas-fir beetle	*Dendroctonus pseudotsugae* Hopkins
Golden buprestid	*Buprestis aurulenta* L.
Pacific dampwood termite	*Zootermopsis angusticollis* (Hagen)
Pacific folding-door spider	*Antrodiaetus pacificus* (Simon)
Ponderous borer	*Ergates spiculatus* (Le Conte)
Redbellied checkered beetle	*Enoclerus sphegeus* F.

Vertebrates:

Beaver	*Castor canadensis* Kuhl
Black-tailed deer	*Odocoileus hemionus* Rafinesque
California red-backed vole	*Clethrionomys californicus* (Merriam)
California slender salamander	*Batrachoseps attenuatus* (Eschscholtz)
Clouded salamander	*Aneides ferreus* Cope
Coho salmon	*Oncorhynchus kisutch* (Walbaum)
Cutthroat trout	*Salmo clarki* Richardson
Oregon salamander	*Ensatina eschscholtzi* Gray
Oregon slender salamander	*Batrachoseps wrighti* (Bishop)
Shrew-mole	*Neürotrichus gibbsi* (Baird)
Steelhead trout	*Salmo gairdneri* Richardson
Trowbridge shrew	*Sorex trowbridgei* Baird

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The interdisciplinary nature of the work reported in this paper evokes the fond memory of our friend, colleague, and teacher, Gerry S. Strickler. Gerry's life of research was dedicated to understanding how different organisms in wildlands interact with each other and their environment. And he left us with a greater appreciation of the importance of cause-and-effect relationships between humans and forests.

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Large, fallen trees in various stages of decay contribute much-needed diversity to terrestrial and aquatic habitats in western forests. When most biological activity in soil is limited by low moisture availability in summer, the fallen tree-soil interface offers a relatively cool, moist habitat for animals and a substrate for microbial and root activity. Intensified utilization and management can deprive future forests of large, fallen trees. The impact of this loss on habitat diversity and on long-term forest productivity must be determined because managers need sound information on which to base resource management decisions.

Keywords: Fallen trees, decay (wood), decomposition, old-growth stands, Douglas-fir, *Pseudotsuga menziesii,* mycorrhizae, soil moisture.

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Costs of Harvesting Beetle-Killed Lodgepole Pine in Eastern Oregon

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Abstract

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The cost of harvesting and recovering round wood logs and whole-tree chips from small diameter lodgepole pine (*Pinus contorta*) infested by mountain pine beetle (*Dendroctonus* sp.) was studied in the Blue Mountains of eastern Oregon in 1979. Mechanized harvest operations were conducted on six study sites totaling 134 acres. The average cost of producing chips was $31.30 per ton, wet, delivered 50 miles from harvest sites. The average cost of logs was $50.28 per ton, wet, delivered the same distance. A gross energy balance indicates that energy required by harvesting was about 3.4 percent of the gross energy content of the delivered products.

Keywords: Logging enterprise costs, lodgepole pine (dead), wood utilization, energy, insect damage (-forest products, mountain pine beetle.

Contents

Introduction

The need for fiber and energy has directed attention to unused forest resources. Accessible, unused forest materials include extensive areas of standing dead timber killed by catastrophic insect epidemics. Extensive stands of dead timber are concentrated in regions of the western United States that produce softwood timber.

One such region is the Blue Mountains of eastern Oregon, where extensive stands of dead lodgepole pine (*Pinus contorta* Dougl. ex Loud.) are the result of an outbreak of mountain pine beetle (*Dendroctonus* spp.) in the 1960's and 1970's (fig. 1). The slow rate of decay prolongs the period of fire hazard associated with dry, dead timber, and the fire hazard increases as standing dead timber collapses and concentrates fuel near the ground. In northeastern Oregon in 1975, there were 1 million acres of lodgepole pine standing dead or threatened with beetle infestation. They contained an estimated 960 million cubic feet of wood.

Dead lodgepole timber, although small in size, can produce both energy and fiber. Trees tend to be concentrated in dense, even-aged stands that become susceptible to beetle kill after they reach 100 years of age. Clearcut harvesting offers a solution to the threat of fire, and the location of lodgepole pine on moderate slopes makes it suitable for mechanized harvesting.

Figure 1.—Dead lodgepole timber stand on harvest study unit 11H.

Purpose of Study

This study was undertaken to determine the potential of standing dead lodgepole timber for fuel and other products and to develop a basis for estimating the cost of mechanically harvesting standing dead lodgepole pine. In 1978, Currier and others had emphasized the need for information on harvest costs to promote the utilization of dead timber.[1]

In addition, the study was intended to:

1. Establish a methodology that could be used to evaluate the economic feasibility of harvesting residues in other forest types;
2. Identify opportunities to further reduce costs of harvesting or to increase value of products by modifying harvesting systems; and
3. Provide information about the ecological effects of mechanized harvesting on nutrient balance and soil compaction. (This information will be documented in a separate report.)

Cooperators

The study was planned and conducted by the Forest Service, U.S. Department of Agriculture, under contract to the Department of Energy. Research and administrative groups within the Forest Service involved in the study included the Pacific Northwest Forest and Range Experiment Station, the Forest Products Laboratory, the Pacific Northwest Region, and the Umatilla National Forest. Also involved were Oregon State University, Eastern Oregon State College, and Chrisstad Enterprises, Inc., an independent logging firm experienced in producing chips from standing lodgepole pine.

The beetle-infested lodgepole timber on the Umatilla National Forest was harvested by Chrisstad Enterprises, Inc., from July to September 1979, under a contract with the Forest Service. Different combinations of log-making and chip-producing methods were tried. The use of machines, labor, and fuel and the amounts of logs and chips produced were monitored by a research team from Eastern Oregon State College. The analysis of the costs of harvesting and delivering products from dead lodgepole pine is based on the cost of harvest operations, the cost of stumpage, and overhead costs chargeable to the harvest operations. Production costs represent actual costs incurred by the independent logging firm that harvested the dead lodgepole pine.

The Study Site

The study was conducted on six separate harvest units which represented about half the harvesting activity of a salvage sale on the Ukiah District of the Umatilla National Forest in the Blue Mountains of northeastern Oregon. The units are identified by numbers assigned in the timber sale contract (4, 46, 42, 26, 5H, and 11H), listed in chronological order of harvest. The units ranged in size from 15 to 32 acres and contained beetle-infested lodgepole pine that ranged in average d.b.h. from 6.3 to 10.0 inches. Estimated volume of standing (live and dead) timber varied from 1,100 to 2,500 cubic feet per acre. Average tree height varied from 40 feet for trees 4 inches in diameter to 80 feet for trees 11 inches or more in diameter. There was little correlation between volume of timber per acre and average diameter because of variations in stand density. Lodgepole stands were generally even-aged, approximately 80 to 110 years old at the time of the initial beetle infestation from 1972 to 1975. Stand characteristics determined by preliminary sampling, are summarized in table 1.

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[1] Currier, Raymond A.; Dykstra, Dennis P.; McMahon, Robert O; and Corder, Stanley E. Potential energy uses for diseased and beetle-killed timber and forest residues in the Blue Mountain Area. Report RLP/2227/T33-1. Prepared for the U.S. Department of Energy. 1978: 58p.

Table 1—Size and volume of standing lodgepole pine timber on 6 harvest units, Umatilla National Forest, 1979

Harvest unit	Size	Average d.b.h.	Estimated total volume	Volume per acre	
	Acres	Inches	Thousand board feet	Thousand board feet	Cubic feet 1/
4	19	8.0	170	8.9	1,800
46	18	6.3	225	12.5	2,500
42	15	7.8	120	8.0	1,600
26	32	9.6	315	9.8	2,000
5H	31	10.0	170	5.5	1,100
11H	19	10.0	160	8.4	1,700

1/Assumes 200 cubic feet of solid wood per thousand board feet of timber. Bark provides an estimated 2 to 3 percent additional volume for fuelwood.

The relatively uniform appearance of dead lodgepole tends to hide physical differences in the timber. Study trees varied in size and number of drying checks. Although average diameter did not vary greatly, size ranged from 3 inches d.b.h. to more than 20 inches in a single stand. Drying checks within a stand ranged from a single, straight radial check to severe, multiple spiral checks. Furthermore, beetle-caused mortality typically does not occur in a single season but tends to accumulate over several seasons, resulting in a range of times since mortality and a variety of defects within a given stand.

Logs and Chips Produced

In all, 197 van loads of chips and 6,249 trimmed house logs and sawlogs were recovered from the six harvest units. Table 2 shows that total wet weight of chips was 4,171 tons, or an average of approximately 31 tons per acre. Total wet weight of logs was 1,385 tons or an average of about 10 tons per acre. Moisture content of logs and chips was determined separately for each harvest unit. Average moisture content was about 17 percent for all logs and about 24 percent for all chips. This contrasts with a general moisture content of 50 percent for material from live lodgepole stands.

Total weight of chips and roundwood was estimated to average 32 tons (ovendry basis) per acre.

Table 2—Logs and chips produced from dead lodgepole pine on 6 study units, Umatilla National Forest, 1979

Harvest unit	Acres	Logs: Number	Logs: Scaled volume	Logs: Weight		Chips: Weight			Chips and logs
			Thousand board feet	Tons wet	Tons ovendry	Tons wet	Tons ovendry	Bone-dry units 1/	Dry tons per acre
4	19	714	46.0	2/ 154.8	3/ 115.0	4/ 802.2	5/ 570.1	6/ 475.1	36.06
46	18	0	0	0	0	707.3	557	464.2	30.94
42	15	0	0	0	0	1088.2	809	674.2	53.93
26	32	1,192	130.9	286.7	259.8	973.9	762.4	635.3	31.94
5H	31	2,360	159.1	481.6	397.8	408	33.1	278.4	23.61
11H	19	1,983	151.5	462.0	378.8	191.1	145.5	121.2	27.59
Total or average	134	6,249	487.5	1,385.1	1,151.4	4,170.7	3,178.1	2,648.4	32.30

1/1 bone-dry unit = 2,4000 pounds or 1.2 ovendry tons.
2/Determined by average moisture content of logs for that harvest unit and dry weight.
3/Estimated from scaled volume at 2.5 tons ovendry per thousand board feet.
4/Determined from load weight at chip purchaser's plant.
5/Calculated from sampled moisture content of each load.
6/Basis of payment, equivalent to 1.2 tons, ovendry weight.

Harvest System and Equipment

The contract logger used modern mechanized harvesting equipment that included feller bunchers (fig. 2), grapple skidders, and chipping equipment. The operator had had several years of experience as an independent logger in the Blue Mountains, including 3 years of harvesting dead lodgepole timber. Prior to the study, he had engaged primarily in producing whole-tree chips (chips from entire trees, including bark).

For this study, the operator acquired a mobile log trimmer and a log loader to allow mechanized production of trimmed roundwood logs. Thus equipped, he had an efficient mechanized system to produce house logs and sawlogs from the larger diameter material, as well as chips from the smaller or lower quality logs. He could have produced posts or fuelwood, but did not because local demand was limited. The study, therefore, focused on a conventional mechanized harvesting system designed to sort out the material most suitable for house logs and sawlogs and to chip the rest.

Figure 2.—Feller buncher harvesting beetle-infested lodgepole timber.

Modifications of Equipment Needed to Produce Logs and Chips

Production decisions were made entirely by the logging operator and crew, based on their perception of markets and product value. Initially, logs and chips were produced simultaneously on the same landing (fig. 3). But the mix of trees available on most units proved unsuited for simultaneous production of logs and chips. Trees large enough for logs often contained deep checks or other defects that made them unsuitable for logs. Production was slowed while trees were sorted according to defect. The simultaneous production of logs and chips on the same landing continued only on unit 4. On all other units the chipper and log trimmer worked separately. On two units (46 and 42) only chips were produced. On units where both logs and chips were produced, the log trimmer was brought in first to sort and trim logs, and the chipper was brought in later to chip the remaining material. On these units, a preliminary examination was made to mark trees for either logs or chips.

Figure 3.—Log trimmer (left), grapple skidder (center), and mobile chipper (right) at a landing site.

Equipment Used

The basic equipment used to harvest all units included rubber-tired feller bunchers and rubber-tired grapple skidders. Feller bunchers sheared individual stems above the ground, accumulating as many as five before laying them on the ground in loads or "turns" for the grapple skidders. Grapple skidders brought the stems to landings in turns of 8 to 15 trees containing 35 to 80 cubic feet of wood. A mobile chipper, a mobile log trimmer, and a log loader were used to process timber into chips and/or logs at the landings. Feller bunchers, grapple skidders, mobile chippers, and log trimmers are referred to as major equipment in this report. A log loader and additional support equipment are referred to as auxiliary equipment.

Auxiliary equipment for the harvest operation included a log loader, a tracked bulldozer, a water tank truck for fire protection, a fuel tank truck for fuel transport and storage, a low-boy trailer, a truck tractor, a road grader, and a fully equipped maintenance truck for field repairs, plus miscellaneous equipment, tools, and pickup trucks.

Products were hauled and delivered by contract haulers, usually at a negotiated price per load, per mile. Loads of chips averaged 22 tons and were hauled 40 to 60 miles to a fiberboard plant. Loads of logs averaged 23 tons and were hauled from 40 to 100 miles to manufacturers of log homes or lumber.

Time Requirements

The operating time for each major equipment item was recorded for each study unit. The auxiliary equipment items listed previously were operated intermittently and were not monitored as closely.

The working schedule was usually from 6:00 a.m. to about 2:30 p.m., Monday through Friday. Scheduled hours of machine use account for the time equipment was on the site during regular working hours (about 8.5 hours per day, 42 hours per week) and are summarized in tables 3 to 8.

Major Equipment Time

Scheduled machine hours for major equipment were the total of productive time, delay time, idle time, and moving time.

Productive time was considered time during which equipment was engaged in productive harvesting activity. Delay time was counted when the crew was present but equipment was not operating. Idle time occurred when the crew was not present and equipment was idle because repair parts were lacking or occasionally because of extreme fire hazard.

A significant amount of time was spent moving equipment from one harvest unit to another. Harvesting each unit took 9 to 22 days, then equipment was moved to another unit. Moving equipment and setting it up on another site took up to half a day. Consequently, some of the scheduled machine hours were used for moving.

The average approximate time required to move equipment from one harvest unit to another, including delays and "start-up" time, were:

	Hours
Feller buncher	2
Grapple skidder	2
Mobile chipper	4
Log trimmer	4
Log loader	4

Variations in the equipment assigned to each harvest unit and the idle time charged to each unit are revealed in tables 3-8. The variations were caused by differences in stand characteristics and decisions by the logging operator. A substantial proportion of the idle time charged to harvest units 4 and 5H may have been the result of inexperience in coordinating log and chip production.

Table 3—Summary of time required for equipment, labor, and administration on harvest unit 4

Equipment	Productive time 1/	Moving time 2/	Hours fueled 3/	Delay time 4/	Crew hours 5/	Idle time 6/	Scheduled hours 7/	Administrative time 8/
				Hours				
Feller bunchers	48.4	4.0	52.4	9.5	61.9	61.6	123.5	
Skidders	61.3	4.0	65.3	8.6	73.9	99.8	173.7	
Chipper	34.5	4.0	38.5	18.0	56.5	48.5	105.0	
Log trimmer	18.2	4.0	22.2	14.5	36.7	51.3	88.0	
Log loader 9/	9.1	--	--	--	--	--	88.0	
Auxiliary equipment 10/	--	--	--	--	--	--	54.8	
Supervisor's time								109.5

1/Productive time = crew present and equipment operating.
2/Moving time = crew present and equipment self-propelled or hauled.
3/Hours fueled = productive time + moving time.
4/Delay time = crew present and equipment not operating.
5/Crew hours = productive time + moving time + delay time.
6/Idle time = crew not present and equipment not operating.
7/Scheduled hours = productive time + moving time + delay time + idle time.
8/Administrative time = total time spent on unit by supervisor.
9/Log loader productive time = one-half log trimmer productive time; log loader scheduled hours = log trimmer scheduled hours.
10/Auxiliary equipment scheduled hours = one-half administrative time.

Table 4—Summary of time required for equipment, labor, and administration on harvest unit 46

Equipment	Productive time 1/	Moving time 2/	Hours fueled 3/	Delay time 4/	Crew hours 5/	Idle time 6/	Scheduled hours 7/	Administrative time 8/
				Hours				
Feller bunchers	68.7	2.0	70.7	8.8	79.5	7.5	87.0	
Skidders	39.4	2.0	41.4	8.5	49.5	10.6	60.5	
Chipper	32.6	4.0	36.6	14.3	50.9	11.6	62.5	
Auxiliary equipment 9/	--	--	--	--	--	--	53.0	
Supervisor's time								106.0

1/Productive time = crew present and equipment operating.
2/Moving time = crew present and equipment self-propelled or hauled.
3/Hours fueled = productive time + moving time.
4/Delay time = crew present and equipment not operating.
5/Crew hours = productive time + moving time + delay time.
6/Idle time = crew not present and equipment not operating.
7/Scheduled hours = productive time + moving time + delay time + idle time.
8/Administrative time = total time spent on unit by supervisor.
9/Auxiliary equipment scheduled hours = one-half administrative time.

Table 5—Summary of time required for equipment, labor, and administration on harvest unit 42

Equipment	Productive time 1/	Moving time 2/	Hours fueled 3/	Delay time 4/	Crew hours 5/	Idle time 6/	Scheduled hours 7/	Administrative time 8/
				Hours				
Feller bunchers	89.3	6.0	95.2	13.0	108.3	11.7	120.0	
Skidders	65.4	4.0	69.4	10.7	80.1	15.9	96.0	
Chipper	40.9	4.0	44.9	16.8	61.7	21.3	83.0	
Auxiliary equipment 9/	--	--	--	--	--	--	49.5	
Supervisor's time								99.0

1/Productive time = crew present and equipment operating.
2/Moving time = crew present and equipment self-propelled or hauled.
3/Hours fueled = productive time + moving time.
4/Delay time = crew present and equipment not operating.
5/Crew hours = productive time + moving time + delay time.
6/Idle time = crew not present and equipment not operating.
7/Scheduled hours = productive time + moving time + delay time + idle time.
8/Administrative time = total time spent on unit by supervisor.
9/Auxiliary equipment scheduled hours = one-half administrative time.

Table 6—Summary of time required for equipment, labor, and administration on harvest unit 26

Equipment	Productive time 1/	Moving time 2/	Hours fueled 3/	Delay time 4/	Crew hours 5/	Idle time 6/	Scheduled hours 7/	Administrative time 8/
				Hours				
Feller bunchers	134.1	6.0	140.1	16.5	156.6	9.4	176.0	
Skidders	123.0	4.0	127.0	20.7	147.7	18.6	166.3	
Chipper	47.9	4.0	51.9	14.4	66.3	7.2	73.5	
Log trimmer	67.8	4.0	71.8	14.0	85.8	13.2	99.0	
Log loader 9/	33.9	--	--	--	--	--	99.0	
Auxiliary equipment 10/	--	--	--	--	--	--	55.3	
Supervisor's time								110.5

1/Productive time = crew present and equipment operating.
2/Moving time = crew present and equipment self-propelled or hauled.
3/Hours fueled = productive time + moving time.
4/Delay time = crew present and equipment not operating.
5/Crew hours = productive time + moving time + delay time.
6/Idle time = crew not present and equipment not operating.
7/Scheduled hours = productive time + moving time + delay time + idle time.
8/Administrative time = total time spent on unit by supervisor.
9/Log loader productive time = one-half log trimmer productive time; log loader scheduled hours = log trimmer scheduled hours.
10/Auxiliary equipment scheduled hours = one-half administrative time.

Table 7—Summary of time required for equipment, labor, and administration on harvest unit 5H

Equipment	Productive time 1/	Moving time 2/	Hours fueled 3/	Delay time 4/	Crew hours 5/	Idle time 6/	Scheduled hours 7/	Administrative time 8/
				Hours				
Feller bunchers	56.5	4.0	60.5	13.0	73.5	49.5	123.0	
Skidders	79.4	4.0	83.4	9.7	93.1	82.9	176.0	
Chipper	53.9	4.0	57.9	13.0	70.9	90.1	161.0	
Log trimmer	51.0	4.0	55.0	7.2	62.2	77.8	140.0	
Log loader 9/	25.5	--	--	--	--	--	140.0	
Auxiliary equipment 10/	--	--	--	--	--	--	134.0	
Supervisor's time								268.0

1/Productive time = crew present and equipment operating.
2/Moving time = crew present and equipment self-propelled or hauled.
3/Hours fueled = productive time + moving time.
4/Delay time = crew present and equipment not operating.
5/Crew hours = productive time + moving time + delay time.
6/Idle time = crew not present and equipment not operating.
7/Scheduled hours = productive time + moving time + delay time + idle time.
8/Administrative time = total time spent on unit by supervisor.
9/Log loader productive time = one-half log trimmer productive time; log loader scheduled hours = log trimmer scheduled hours.
10/Auxiliary equipment scheduled hours = one-half administrative time.

Table 8—Summary of time required for equipment, labor, and administration on harvest unit 11H

Equipment	Productive time 1/	Moving time 2/	Hours fueled 3/	Delay time 4/	Crew hours 5/	Idle time 6/	Scheduled hours 7/	Administrative time 8/
				Hours				
Feller bunchers	74.1	4.0	78.1	9.4	87.5	0	82.5	
Skidders	53.9	2.0	55.9	10.6	66.5	15.5	82.0	
Chipper	21.0	4.0	25.0	4.5	29.5	0	29.5	
Log trimmer	47.9	4.0	51.9	16.1	68.0	15.5	83.5	
Log loader 9/	24.0	--	--	--	--	--	83.5	
Auxiliary equipment 10/	--	--	--	--	--	--	57.8	
Supervisor's time								115.5

1/Productive time = crew present and equipment operating.
2/Moving time = crew present and equipment self-propelled or hauled.
3/Hours fueled = productive time + moving time.
4/Delay time = crew present and equipment not operating.
5/Crew hours = productive time + moving time + delay time.
6/Idle time = crew not present and equipment not operating.
7/Scheduled hours = productive time + moving time + delay time + idle time.
8/Administrative time = total time spent on unit by supervisor.
9/Log loader productive time = one-half log trimmer productive time; log loader scheduled hours = log trimmer scheduled hours.
10/Auxiliary equipment scheduled hours = one-half administrative time.

Auxiliary Equipment Time

The time required to operate auxiliary equipment was short compared to that needed for major equipment. The log loader, for example, was operated only intermittently to sort and load logs.

The tracked dozer was used to clear spur roads, create landings, clean up after harvest, and occasionally to move logs or push stalled vehicles. The road grader was used occasionally to maintain roads. The truck tractor was used to move chipvans at the landings, especially to position the vans at the chipper. The truck tractor was used also to haul equipment on the low-boy trailer and to haul the chipper from one harvest site to another. The pickup trucks and maintenance truck were used to transport parts, supplies, and personnel. The watertank fire truck was used occasionally for dust abatement.

Time required of auxiliary equipment was not monitored continuously; scheduled time requirements were assumed to be one-half the total scheduled time of major equipment on each study unit (tables 3-8). Productive machine hours (actual use) for each piece of auxiliary equipment are estimated as follows:

Equipment	Hours of use
Tracked dozer	3 per landing site (clear landing) 3 per harvest unit (site clean-up, other duties)
Maintenance truck	1.5 per scheduled day
Road grader	3 per harvest unit
Truck tractor	0.5 per loaded chipvan 2 moving dozer per unit 2 moving chipper per unit
Fire truck	3 per landing site
Fuel tank truck	1 per scheduled day
Pickup truck (2 trucks)	2 per scheduled day (each truck)
Chain saws	1 per harvest unit

The number of landings, scheduled days of work, truckloads of logs and vanloads of chips required were as follows:

Harvest unit	Landings	Days	Vanloads	Truckloads: Saw logs	Truckloads: House logs
4	1	9	37	6	—
46	2	13	34	—	—
42	2	12	49	—	—
26	2	14	47	7	7
5H	2	22	21	14	14
11H	3	14	9	9	9

Labor and Supervision Time

Labor requirements varied with the types of equipment used. In general, one operator was required for each feller buncher, skidder, mobile chipper, log trimmer, and log loader. Crew members operated auxiliary equipment as required. The crew member who operated the chipper often operated the truck tractor used to reposition chipvans on landings. The log trimmer crew member operated the tracked dozer occasionally to maintain landings and spur roads. Operators of the feller buncher and skidder occasionally used chain saws to remove large snags. Additional duties of the crew included post-harvest cleanup of the site, occasional road maintenance, and dust abatement on the landings with the watertank fire truck.

Two maintenance people were regularly assigned to provide back-up maintenance of harvesting equipment. One was regularly assigned to the maintenance shop facility. The other was assigned to both shop and the field.

The foreman in charge of harvesting operations provided general supervision and occasionally performed such services as transporting spare parts and fuel or maintaining equipment. He also operated equipment for brief periods. The logging contractor occasionally assisted the foreman in supervising operations but usually performed administrative duties.

The logging contractor, the foreman, and the maintenance personnel were responsible for harvest activities on both study and nonstudy units during the study period. Because activity on the study units represented about half the total activity, only half the time of the above personnel was charged to study units.

Costs

Harvest Costs

All cost estimates derived in this study are specific to the harvest operation studied in the Blue Mountain area in 1979. Extrapolation of results to other harvest operations or different times should be limited. The production times, do, however, illustrate the factors that must be considered in any cost analysis, and the techniques used here to estimate costs are applicable to any harvesting situation.

Total harvest cost is an aggregate of direct and indirect costs identified during harvest of the study units and includes the following breakdown:

Equipment —

1. Capital recovery or rental (ownership costs)
2. Maintenance (parts, supplies, and repairs)
3. Labor (wages and fringe benefits)
4. Fuel and lubricants
5. Insurance and local taxes

Operating overhead—

1. Administrative, supervisory, and maintenance
2. Stumpage, road maintenance, and environmental protection fees
3. Contracted transportation

Capital Costs

Investments in equipment and facilities are estimated on the assumption that they were made in 1979. Some logging operators in the Blue Mountains believe that acquiring used or rebuilt equipment is economical for certain items that are operated only intermittently. Equipment that is worked heavily or continuously should be acquired new if possible. Whether equipment is acquired new generally depends on the type and scale of operation and on the availability of investment capital. Items of equipment and facilities used on the study units are listed below, along with indications of whether they were acquired new or used. Costs are estimated as of 1979 for the general region of the Blue Mountains.

Equipment	Horsepower	New/used	Cost
			(dollars)
Mobile chipper	380	new	165,000
Mobile log trimmer	160	new	154,000
Feller buncher	105	new	75,000
Grapple skidder	120	new	70,000
Tracked dozer	200	used	70,000
Log loader		used	30,000
Maintenance truck, tools		used	25,000
Road grader	135	used	22,000
Low-boy trailer		used	16,000
Truck tractor		used/rebuilt	12,000
Fire truck/water tank		used	4,000
Fuel tank truck		used/rebuilt	4,000
Miscellaneous equipment (chain saws)			1,000
Maintenance shop facility and tools			55,000
Pickup truck		leased	150/month

Annual capital recovery cost is calculated by the so-called exact capital recovery formula, as follows:

$$\text{Annual Capital Recovery} = (P - L) \left(\frac{i(1+i)^n}{((1+i)^n - 1)}\right) + (i)(L)$$

Where, n = number of years of useful life or capital recovery period,
P = amount of initial investment,
L = salvage value at the end of n years,
and, i = interest rate of capital or borrowed money.

Hourly costs to recover capital investment in equipment are based on estimated annual costs and time scheduled annually for use of each item. Major equipment (feller bunchers, skidders, chipper, and log trimmer), are usually scheduled for full-time operation daily. Mechanized harvesting in the Blue Mountains, however, is limited to about 8 months of the year because of weather or soil conditions in winter and spring. Scheduled machine hours are therefore limited to about 1,400 hours per year, based on a 40-hour work week, and this is the number used in this analysis for all equipment.

The expected useful life of new diesel-powered timber-harvesting equipment is typically about 10,000 hours. With potential operating time set at 1,400 hours per year, an appropriate capital recovery period is 7 years, and this period was used for equipment in this analysis. The salvage value of all equipment is set at 10 percent of initial investment at the end of 7-years.

Maintenance Costs

Costs for parts replacement, supplies, and outside repairs vary with equipment. Maintenance costs increase as equipment ages or is used more heavily. A formula that can be used to estimate average annual maintenance costs for harvesting equipment is derived from a commonly used rule of thumb. It suggests that total maintenance costs over the life of a piece of equipment are roughly 50 percent of the purchase price for parts and supplies, and is expressed as follows:

$$\text{Annual maintenance cost} = \frac{(F)\quad(P)}{n};$$

where, F is maintenance cost factor (percent of purchase price),

P is the initial purchase price,

and, n is the number of years of useful life.

One local equipment supplier in the Blue Mountains suggested that an appropriate cost factor for the above formula would be 45 percent. Information provided by the logging operator and observations of maintenance required during the study suggest that the following factors are appropriate for calculating annual maintenance cost:

	Percent of initial cost
Chipper, skidders, feller bunchers	55
Log trimmer, loader, dozer, truck tractor, and fire truck	45
Other equipment items	30

The cost of tire replacement is an additional major expense for certain equipment. The following summary indicates the cost of replacing tires and assumptions about average tire life used in this analysis:

Equipment	Tires per vehicle	Replacement cost per tire	Average tire life
		1979 dollars	*Years*
Grapple skidder	4	900	1.0
Feller buncher	4	900	.5
Mobile chipper	8	350	3.5
Log trimmer	4	900	2.0
Log loader	6	500	3.5
Maintenance truck	6	150	3.5
Road grader	4	900	3.5
Low-boy trailer	8	200	3.5
Truck tractor	10	200	1.0
Fire truck	6	150	3.5
Fuel truck	4	100	3.5
Pickup truck	4	150	2.0

Replacement costs are averaged on both annual and hourly bases. Average annual cost is estimated by the following formula:

$$\text{Average annual cost of replacing tires} = \frac{\left(\text{Number of tires per set}\right)\left(\text{Cost of each tire}\right)}{\text{Years of average tire life}}.$$

Labor Costs

Cost of labor to operate equipment is an additional expense computed in the hourly costs for major equipment. Cost of supervision and maintenance are included in overhead costs. Labor rates include hourly wages plus fringe benefits, coverage required by State Workers' Compensation laws, and Social Security employer contributions, amounting altogether to 57 percent of basic wages.

Labor rates used in this study are those that prevailed in the Blue Mountains region in 1979 as follows:

	Wage	Fringe benefits and employer's contributions	Total
		Dollars per hour	
Operators of log trimmer and chipper	9.50	5.50	15.00
Operators of feller buncher, skidder, loaders, maintenance personnel	8.75	5.00	13.75

Labor rate for the supervisory foreman is $30,000 per year.

Fuel and Lubricant Costs

Fuel consumption and lubricant requirements of major equipment were monitored periodically and are reported as observed. All major equipment had diesel engines. Several items had been in service for a number of years. Shearing and chipping is considered to be generally more difficult in dry, dead lodgepole than in live timber. Difficulty of terrain and elevation (about 4,000 feet) may also have affected fuel consumption.

Lubricant requirements may reflect special difficulties or requirements peculiar to harvesting dead timber in the Blue Mountains, or problems specific to the particular equipment. Requirements reported here are based on limited data and may have limited application to other harvest operations, even under similar conditions. Fuel and lubricant requirements for major equipment were as follows:

	Horsepower	Fuel	Oil	Grease
		Gallons per hour	*Gallons per day*	*Pounds per day*
Feller buncher	105	7	1.0	1.0
Grapple skidder	120	7	1.5	.3
Log trimmer	160	6.5	.6	1.0

The mobile chipper (380 hp) used 12.5 gallons of fuel per van load of chips.

Overhead Costs

Annual administrative, supervisory, and maintenance overhead costs for the entire logging operation in 1979 were as follows:

Administrative overhead	$ 65,000
Supervisory overhead	35,000
Maintenance facility (capital recovery, taxes, insurance)	7,900
Maintenance labor	46,800
Total	$154,700

Dividing the total annual cost by 1,400 (hours per year of scheduled time) gives a cost of $110.50 per scheduled hour. Because the study units made up only half the total harvest operation, $55.25 per hour of scheduled time was used to figure the cost for administrative, supervisory, and maintenance overhead.

Administrative overhead includes salaries and travel expenses of personnel who negotiate contracts and arrange product sales. Supervisory overhead includes the salary and travel and planning expenses of the foreman. A 45-year period is used to derive capital recovery costs of the maintenance building and 7 years for maintenance facility equipment. Maintenance personnel are assumed to be employed for an average of 1,700 hours per year.

Hourly Costs

The hourly costs of major harvesting activities (felling and bunching, skidding, chipping, log-making and loading) are calculated by determining the hourly cost of operating each piece of major equipment and applying these costs to the machine hours listed for each harvest unit in tables 3-8. Hourly costs for major equipment are reported in table 9. Costs of capital, insurance, taxes, maintenance, and tires are calculated in dollars per scheduled hour. Costs of labor are per hour of payroll time. Costs of fuel and lubricants are per productive hour of actual operation.

Hourly costs for auxiliary equipment are tabulated in table 10. No labor costs are included because auxiliary equipment was operated intermittently by operators of major equipment and all crew labor is accounted for in the costs of major equipment to which crew members were regularly assigned.

Harvest Costs by Harvest Unit

The total costs for harvesting each of six units are tabulated in table 11. Costs are based on the number of scheduled machine hours, crew hours, and hours fueled for each type of machine and the appropriate hourly cost (table 9). Auxiliary equipment costs are determined from tables 3-8 and 10 in a similar manner.

Administrative, supervisory, and maintenance costs for each harvest unit were determined by multiplying the administrative hours on that unit (table 3) by the hourly overhead cost of $55.25.

Additional overhead expenses include Forest Service stumpage fees, road maintenance, and environmental protection fees. A stumpage price of $0.50 per thousand board feet was paid for the salvage sale that included the six study units. A conversion factor commonly used for small timber sales in the Blue Mountains is: one thousand board feet, log scale, is equivalent to 2.5 ovendry tons. This conversion gives a stumpage cost of $0.20 per ovendry ton of products recovered. Additional fees for road maintenance, slash disposal, and erosion control are also assessed to logging operations. On the timber sale that included the study units these additional fees amounted to $5.19 per thousand board feet, or about $2.10 per ovendry ton of products recovered. Total Forest Service fees, therefore, amounted to $2.30 per ovendry ton of products recovered.

Harvest Costs of Logs and Chips Compared

To calculate harvest costs separately for logs and chips, we assigned appropriate costs to log harvest and chip harvest (table 12). The cost of operating the chipper was assigned to chips; the cost of the log trimmer and log loader was assigned to logs. After these costs were subtracted from total costs for each harvest unit, the remaining costs of felling, bundling, and skidding logs to landings were prorated to logs and chips on the basis of wet weight (table 2).

To find costs to be prorated on harvest unit 4, for example, we subtracted log costs and chipping costs from total harvest costs of $28,148, leaving $18,237 to be prorated. The wet weight of logs was 154.8 tons, the wet weight of chips, 802.2 tons, or 16.2 and 83.8 percent, respectively, of total products. Multiplying $18,237 by 16.2 (the percentage of green log weight) gave $2,954 as the share of harvest costs assigned to log production. Adding the costs of log trimming ($3,263), log loading ($1,128), and the prorated share of other harvest costs ($2,954) gave a total cost of $7,705 for harvesting logs. Dividing by units of logs produced (154.8 wet tons) gave a unit cost of $49.77 per wet ton. The cost per board foot of logs was $7,705 divided by 46.0 (thousand board feet produced on unit 4) for a cost of $74.16 per thousand board feet.

Table 9—Hourly costs for major equipment acquired in 1979, based on a capital recovery period of 7 years and interest at 12 percent, salvage value at 10 percent of investment, and annual scheduled machine hours of 1,400

	Per scheduled hour					Per crew hour	Per productive hour
Equipment	Capital recovery	Insurance 1/	Local taxes 2/	Maintenance 3/	Tires	Labor	Fuel and lubrication 4/
				Dollars			
Feller buncher 5/	11.21	0.82	0.49	4.21	4.77	13.75	5.20
Grapple skidder 6/	10.46	.77	.46	3.92	2.20	13.75	5.38
Mobile chipper 7/	24.66	1.81	1.09	9.26	.29	15.00	11.25
Log trimmer 8/	23.01	1.69	1.01	7.08	.92	15.00	4.80
Log loader 9/	4.48	.32	.21	1.38	.31	13.75	2.63

1/Insurance = 2.5 percent of average investment.
2/Local taxes = 1.5 percent of average investment.
3/Parts, supplies, outside repairs.
4/Fuel at $0.70 per gallon, oil at $2.40 per gallon.
5/Cost $75,000 new.
6/Cost $70,000 new.
7/Cost $165,000 new.
8/Cost $154,000 new.
9/Cost $30,000 used.

Table 10—Hourly costs for auxiliary equipment

	Per scheduled hour					Per productive hour
Equipment	Capital recovery	Insurance and taxes	Maintenance	Tires (or tracks)	Total	Fuel and lubricants
			Dollars			
Tracked dozer	10.46	1.23	3.22	0.20	15.11	5.70
Maintenace truck	3.74	.44	.46	.09	4.73	3.75
Road grader	3.29	.39	.67	.37	4.72	3.38
Low-boy trailer	2.39	.28	.48	.16	3.31	--
Truck tractor	1.79	.21	.55	1.22	3.77	6.00
Fire truck	.60	.07	.18	.09	.94	3.75
Fuel tank truck	.06	.07	.18	.04	.89	3.75
Miscellaneous (chain saws)	.15	.02	.03	--	.20	.38
Pickup truck rental	.94	--	.21	.06 x 2	2.42	3.00
Total per scheduled hour					36.09	

Table 11—Summary of harvest costs by harvest unit

Harvest unit	Equipment 1/ Feller bunchers	Grapple skidders	Mobile chipper	Log trimmer	Log loader	Auxiliary equipment	Overhead 2/	Fees 3/	Total
	Dollars								
4	3,779	4,461	5,160	3,623	1,128	2,361	6,050	1,576	28,138
46	3,331	1,986	3,465	0	0	2,401	5,857	1,281	18,321
42	4,564	3,184	4,557	0	0	2,298	5,470	1,861	21,934
26	6,666	5,675	4,251	4,969	1,943	2,554	6,105	2,351	34,514
5H	3,969	4,863	7,274	5,916	1,871	5,489	14,807	1,683	45,872
11H	3,490	2,675	1,638	4,083	1.568	2,549	6.381	1,206	23,590

1/Equipment costs include hourly costs for major equipment (table 9) multiplied by number of machine hours (tables 3-8). Auxiliary equipment costs include scheduled hours (tables 3-8) multiplied by cost per scheduled hour (table 10, bottom line) plus productive hours for each piece of equipment multiplied by cost per productive hour (table 10).
2/Administrative time (tables 3-8) multiplied by $55.25 per hour (half the total hourly overhead costs).
3/Ovendry tons of product (table 2) multiplied by Forest Service fees of $2.30 per ovendry ton.

Table 12—Harvest costs prorated to logs and chips by percent weight

Harvest unit	Costs Total	Chipper	Trimmer	Loader	Amount prorated	Total weight Logs	Total weight Chips	Weight proportion Logs	Weight proportion Chips	Total costs Logs	Total costs Chips	Cost per ton Logs	Cost per ton Chips
	Dollars					Wet tons		Percent		Dollars			
4	28,148	5,160	3,623	1,128	18,237	154 8	802.2	16.2	83.8	7,705	20,443	49.77	25.48
46	18,321	0	0	0	0	0	707.3	0	100.0	0	18,321	0	25.90
42	21,934	0	0	0	0	0	1,088.2	0	100.0	0	21,934	0	20.16
26	34,504	4,251	4,969	1,943	23,341	286.7	973.9	22.7	77.3	12,210	22,294	42.59	22.89
5H	45,482	7,274	5,916	1,871	30,811	481.6	408.0	54.1	45.9	24,456	21,416	50.78	52.49
11H	23,590	1,638	4,083	1,568	16,301	462.0	191.9	70.6	29.4	17,160	6,430	37.14	33.51
Total or average	172,979	18,323	18,591	6,510	--	1,385.1	4,170.5	--	--	61,531	110,838	44.42	26.58

The cost of producing chips on harvest unit 4, for example, included the chipping cost of $5,160 (table 12) plus costs prorated to chips. Prorated cost was $18,237 multiplied by 0.838 (chip weight percent), or $15,283. The total harvest cost of chips then was $20,443 ($15,283 plus $5,160). The cost per wet ton was $25.48 ($20,443 divided by 802.2). Costs of chips per ovendry ton was found by dividing total costs of chip harvest ($20,443) by 570.1 (dry tons from table 2) to give a cost of $35.86 per ovendry ton. Costs per bone-dry unit of 2,400 pounds was $35.86 multiplied by 1.2, or $43.02.

Costs of producing logs and chips from all harvest units are summarized in table 12.

Transportation Costs

Transportation represents the final expense in the total cost of delivered chips or log products. Most delivery points were located 50 miles from harvest units. The rate for hauling logs was about $400 per day, per truck. Trucks could deliver about three loads per day at a cost of approximately $133 per truckload. Chips were hauled in vans at $2.00 per mile one way ($2 per loaded mile). Transportation costs, based on total truckloads and vanloads of materials transported from study units, are reported in table 13.

Delivered Costs

Delivered costs (table 14) are the sum of harvest costs plus transportation costs. The delivered costs of logs ranged from a low of $43.19 per wet ton (unit 11H) to a high of $56.57 (unit 5H). The average cost for all units was $50.28. The delivered cost of logs is also shown per ton, ovendry, and per thousand board feet.

The delivered cost of chips varied from $30.10 per ton, wet (unit 4) to $57.64 (unit 5H). The average cost for all units was $31.30. The delivered cost of chips is also shown per ton, ovendry, and per bone-dry unit (2,400 pounds).

Variables That Affect Product Costs

Timber Characteristics

Harvest costs are determined to some extent by stand characteristics. Size of timber, tree denisty, and stand volume affect the efficiency of harvesting and influence costs. Two of the six study units (46 and 11H) provide examples of differences in characteristics of lodgepole pine, the only species harvested on the salvage sale. Characteristics of the timber were reported accurately in a survey done before the harvest. It provides the following detail:

	Unit 46	Unit 11H
Average number of stems per acre	452	337
Average stem diameter (d.b.h. in inches)	5.93	8.52
Basal area (square feet per acre)	84.03	129.42
Stem volume (cubic feet per acre)	2,469.2	3,186.8
Average height (feet)	54.9	69.0
Dry weight of biomass (tons per acre):		
Stems and bark	30.87	40.37
Branches and needles	5.05	5.76
Average stem volume (cubic feet per stem)	5.46	9.45

Without reference to the preharvest survey data, the logging operator decided to recover roundwood and chips from unit 11H and only chips from unit 46. He based his decision only on observation of timber size, and it appeared to be supported by data from the survey indicating larger average stem diameter and average stem volume on unit 11H, compared with unit 46.

Table 13—Transportation costs by harvest unit

Unit	Logs produced				Chips produced				Costs 1/			
									Logs		Chips	
	Number of loads	Tons, wet	Tons, ovendry	Thousand board feet	Number of loads	Tons, wet	Tons, ovendry	Bone-dry units	Per ton, wet	Per thousand board feet	Per ton, wet	Per bone-dry unit
									--------Dollars--------			
4	6	154.8	115.0	46.0	37	802.2	570.1	475	5.16	17.35	4.61	7.79
46	--	--	--	--	34	707.3	557.0	464	--	--	4.81	7.33
42	--	--	--	--	49	1,088.2	809.0	674	--	--	4.50	7.27
26	13	286.7	257.8	103.9	47	973.9	762.4	635	6.03	16.40	4.83	7.40
5H	21	481.6	397.8	159.1	21	408.0	334.1	278	5.80	17.55	5.15	7.55
11H	21	462.0	378.8	151.5	9	191.1	145.5	121	6.05	18.43	4.71	7.44
Total or average 2/	61	1,385.1	1,149.4	460.5	3/197	4,170.7	3,178.1	2,647	5.76	17.43	4.77	7.46

1/Costs are based on $133 per load of logs and $100 per load of chips for an average haul of 50 miles.
2/Loads of logs averaged 22.7 tons, wet (18.9 tons, ovendry), and 7.55 thousand board feet; loads of chips averaged 21 tons, wet (16 tons ovendry) or 13.4 bone-dry units. Loads of logs or chips from live lodgepole pine timber would average more nearly 4.5 thousand board feet or 8.75 bone-dry units, based on wet weight twice that of dry weight (50 percent moisture).

Table 14—Delivered cost of logs and chips, by harvest unit and unit of production

Harvest unit	Production				Costs			Delivered cost per unit of production			
	Tons wet	Tons ovendry	Bone-dry unit 1/	Thousand board feet 2/	Harvest	Trans-portation	Total harvest	Ton wet	Ton ovendry	Thousand board feet	Bone-dry unit
					--------Dollars--------						
					LOGS						
4	154.8	115.0	--	046.0	7,705	798	8,503	54.93	73.94	184.85	--
26	286.7	259.8	--	103.9	12,210	1,729	13,939	48.62	53.65	134.16	--
5H	481.6	397.8	--	159.1	24,456	2,793	27,248	56.57	68.50	171.26	--
11H	462.0	378.8	--	151.5	17,610	2,343	19,953	43.19	52.67	131.70	--
All units	1,385.1	1,149.4	--	460.5	61,531	7,663	69,643	50.28	60.59	151.23	--
					CHIPS						
4	802.2	570.1	475.1	--	20,443	3,700	24,143	30.10	42.35	--	50.82
46	707.3	557.0	464.0	--	18,321	3,400	21,721	30.17	39.00	--	46.80
42	1,088.2	809.0	674.0	--	21,934	4,900	26,834	24.66	33.17	--	39.80
26	973.9	762.4	635.0	--	22,294	4,700	26,994	27.72	35.41	--	42.49
5H	408.0	334.1	278.0	--	21,416	2,100	23,516	57.64	70.39	--	84.47
11H	191.1	145.5	121.0	--	6,430	900	7,330	38.36	50.38	--	60.45
All units	4,170.7	3,178.1	2,647.1	--	110,838	19,700	130,538	31.30	41.07	--	49.31

1/1 bone-dry unit = 2,400 pounds or 1.2 tons ovendry.
2/1,000 board feet = 2.5 tons ovendry.

Costs of harvesting timber of smaller diameter are usually expected to be higher because more stems must be handled per unit of production. Results on units 46 and 11H are somewhat contradictory. Total harvest costs of $18,321 for unit 46 and $23,590 for unit 11H (table 11) are proportional to the estimated total dry weights of stems and bark for the two units. Total recovery of products from unit 46, however, was 557 dry tons of chips or 30.94 dry tons per acre. This was 100 percent of the estimated biomass (excluding branches and needles). But on unit 11H, only 379 dry tons of logs and 145 dry tons of chips (total 524 dry tons) or 27.59 dry tons per acre were recovered. This was only 68 percent of the estimated biomass.

This apparent contradiction in the expected relationship between timber size and harvest cost may have resulted from the combined factors of a limited number of study units and the operator's experience. As noted previously, the operator had had considerable previous experience in converting all stems to chips, as he did on unit 46, but no experience in sorting for both log and chip production, as on unit 11H.

Moisture Content

Moisture content may have conflicting effects on costs. Lower moisture content means lower weight per volume and permits trucks to haul larger loads of logs or chips, thus reducing transportation costs. Chipping dry, dead wood, on the other hand, increases wear on the chipper knife and increases costs directly, because parts must be replaced earlier and/or sharpened, and, indirectly, by increasing delay time. Dry branches from dead trees are stiffer than those from green trees and more likely to puncture tires on feller-bunchers and skidders. Earlier replacement of tires and time lost for tire changes add to harvest costs.

The moisture content of logs in this study was determined by cutting cross-sectional samples from a number of logs on each harvest unit. These were weighed before and after ovendrying. The weight lost, as a percent of initial weight (wet) is the moisture content. Average moisture content of logs from harvest units 4, 26, 5H and 11H was 25.7, 9.4, 17.4, and 18.0 percent, respectively. These figures were used to convert ovendry weight of logs to wet weight as shown in tables 2 and 13. Dry weight of logs was determined by multiplying the scaled cubic volume by a density of 25 pounds per cubic foot. At 200 cubic feet per thousand board feet (gross log scale) this conversion amounts to 2.5 dry tons per thousand board feet.

In all, the 61 loads of logs averaged 7.75 thousand board feet, gross log scale. At an average moisture content of 17 percent (all logs), the wet weight per load was 22.7 tons. For live lodgepole pine at 50 percent moisure content (50 pounds per cubic foot) a maximum load of 22.7 tons, wet, would correspond to 4.54 thousand board feet, gross log scale, or less than 60 percent of the volume of a load of dead lodgepole pine.

Each vanload of chips was weighed at the chip purchaser's plant. A sample of chips was taken from each load to determine the average moisture content. The measured moisture content was then used to calculate the dry weight of chips and the number of bone-dry units (2,400 pounds) as the basis for payment.

The average moisture content of chips from harvest units varied from 18 percent on unit 5H to 29 percent on unit 4. Overall moisture content averaged 24 percent, compared with 17 percent for logs. The difference can be attributed largely to the fact that the relatively smaller stems going to chip production included a higher proportion of material from live trees.

Energy Comparisons

A person considering the production of wood fuel from dead lodgepole pine must compare the energy that will be expended in harvesting with the potential energy that can be recovered from fuel.

In examining this question, we have assumed that conventional mechanized harvest systems, as used in eastern Oregon in 1979, will remain the most economical and efficient systems in the foreseeable future, and that all direct energy used during harvesting and transporting it is derived from oil. It is conceivable, however, that alternative fuels such as alcohol or wood gas could replace some of the oil fuel without greatly affecting the harvest system. We have also assumed that all harvesting material is recovered as chips.

Producing Chips Only

Whole-tree chips could have been produced exclusively from all harvest units in this study without significantly modifying the harvesting system. Felling, bucking, and skidding operations would have been the same. Trimming, loading, and transportation of logs would have been eliminated. Operation of the mobile chipper and truck tractor would have increased in proportion to the additional weight of chips produced. All other activities, including use of auxiliary equipment, would have remained the same.

The following tabulation shows amounts of chips that would have been produced if chips had been the only product from the six study units. Tons of wet chips include the wet weight of logs that were actually produced from four of the units (4, 26, 5H, and 11H). Tons of ovendry chips were calculated on the basis of the moisture content of logs that were produced.

Harvest unit	Wet	Ovendry	Vanloads
	Tons		
4	957.0	685.1	45
46	707.3	557.0	34
42	1,088.2	809.0	52
26	1,260.6	1,022.2	60
5H	889.6	731.9	42
11H	653.1	524.3	31
Total	5,555.8	4,329.5	264

Energy Required for Harvesting and Transportation

Energy required for harvesting and transportation is mainly in the form of diesel oil but includes minor quantities of gasoline, lubricating oil, and grease. The average amounts of energy required to harvest and deliver a ton of ovendry chips is estimated in gallons of diesel fuel and British thermal units (Btu's).

	Gallons	Btu's
Feller buncher	0.782	109,000
Grapple skidder	.701	98,000
Mobile chipper	.745	104,000
Auxiliary equipment	.808	113,000
Transport and delivery	1.192	167,000
Total	4.228	591,000

Fuel requirements are converted to gross energy on the basis of 140,000 British thermal units per gallon of oil. In International System (SI) units, joules per kilogram are obtained by multiplying Btu per ton by a factor of 1.1639.

The total energy requirements shown in table 15 are based on the simulated production of chips only. Some minor indirect energy inputs are not included. Energy output is based on the heating value of lodgepole pine at 8,700 Btu's per pound, ovendry, or 17.4 million Btu's per ton. The energy balance indicates that gross energy required to harvest and deliver chips from dead lodgepole pine represents only 3.4 percent of the gross energy output of the chips produced. From an energy standpoint, harvesting dead lodgepole for fuel appears likely to become more practical and economical as energy (particularly fuel oil) becomes more expensive, all other considerations being the same.

More important from an energy standpoint is the higher efficiency achieved in burning dead lodgepole pine, compared with most other wood fuels. Lodgepole pine at an average moisture content of 20 percent should burn with about 75 percent efficiency. By comparison, oil is generally fired at 80 percent efficiency and fuel from live timber at 65 percent or less efficiency.

Table 15—Estimates of energy that would be required to harvest and deliver dead lodgepole pine from 6 harvest units as ovendry chips

Harvest unit	Chip production	Feller buncher	Grapple skidder	Mobile chipper	Auxiliary equipment	Transport van 1/	Total	Equivalent per ton of chips
	Ovendry tons	Gallons of diesel oil 2/						
4	685.1	348	441	538	451	860	2,638	3.85
46	557.0	494	283	425	469	680	2,351	4.22
42	809.0	642	470	613	573	980	3,278	4.05
26	1,022.0	946	884	750	658	1,200	4,456	4.36
5H	731.9	406	517	525	811	840	3,153	4.31
11H	524.3	533	387	375	583	600	2,433	4.64
Total or average	4,329.3	3,369	3,036	3,226	3,545	5,160	18,309	4.23

1/Estimated at 20 gallons per 50-mile trip.
2/Petroleum fuels and lubricants.

The economic feasibility of harvesting dead lodgepole for fuel depends on harvest costs and market opportunities. Buyers who intend to use dead lodgepole for fuel must pay the market price. Although the search for alternative energy sources has led to greater consideration of wood as fuel, use of wood for other products has also increased. Thus, the market determines which products are produced from dead lodgepole. A buyer interested in using dead lodgepole for fuel may represent only one market opportunity for a logging operator.

Opportunities for Marketing Dead Lodgepole Pine

Sawmills designed and specially equipped to process timber smaller than 12 inches in diameter have recently appeared in many areas of the West. Operators of these sawmills encounter some difficulties and occasional advantages in processing beetle-killed lodgepole pine. The principal difficulties are that less lumber is recovered from dead timber that has drying checks and a disproportionate amount is low-grade lumber. Several studies of lumber recovery and problems associated with utilization of dead timber in sawmills have been reported (1, 2, 3).

House Logs

A relatively new industry in many areas of the West is producing commercial log homes. About 100 independent firms were manufacturing log homes in 1978 (4). Typically, these firms operate facilities located near the timber source. In the West, these firms usually manufacture and assemble log homes at their manufacturing facilities, then disassemble the structures and ship to buyers for on-site construction. Log-home packages and components are often shipped several hundred miles from manufacturing facilities. Log homes have a variety of uses, ranging from recreational homes to primary residences and commecial buildings such as stores and restaurants. Modern log homes have a certain rustic charm, generally appear to be solidly built, and are often attractive.

Some firms prefer dead lodgepole as a raw material because it is already dry and, therefore, maintains dimensional stability. Drying checks appear to pose serious problems for some firms, but not for others.

Paper and Board Products

Pulpmills are major consumers of wood in the West. Whole-tree chips from dead lodgepole pine are suitable for most types of paper or composition board products. In the West, however, more than three-fourths of the raw material for the pulp and board industries comes from residue of the lumber and plywood industries.

The unique dependence of the pulp industry in the West on sawmills, veneer mills, and plywood mills for raw material, results in a relationship between lumber production and the demand for chips by the pulp industry. When the housing market is strong, sawmills produce large quantities of lumber and generate large quantities of residue that becomes a source of low-cost raw material for the pulp industry. But, when the housing market slumps, lumber and residue production declines and prices for pulpmill raw material are likely to increase. When that occurs, loggers of marginal quality timber of low value may find it advantageous to produce chips rather than logs.

Wood Fuel

Although the heat energy recoverable from different fuels can be compared directly, the comparative economic values of fuels are more ambiguous. If one ton, ovendry weight, of dead lodgepole pine has heating value equivalent to about 106 gallons of fuel oil, and fuel oil sells for $1 per gallon, the maximum value of the wood would be $106 per ton. Fuelwood, however, is less convenient than oil because it is bulky and requires large storage areas. Combustion systems for fuelwood often require more costly equipment, maintenance, and operation than oil- or gas-fired systems of the same heating capacity. The value of fuelwood is therefore generally lower than would be indicated by direct comparisons of heating values of other types of conventional fuels, with the possible exception of coal.

One alternative to direct combustion of harvested wood chips is to produce densified wood fuel. In this process wood is hammermilled to small particles, then compacted or forced through dies to produce densified fuel, commonly referred to as "pellets," "briquets," or "stoker fuel." Densification does not increase the heating value of wood per unit of weight but does increase the density or weight per unit of volume. Densification can triple the weight per unit of volume compared with whole-tree chips.

Densification causes three important effects. First, it reduces transportation costs where weight is not a limiting factor, as it is in over-the-road transportation, where weight limits the amount of material than can be hauled per load. In rail or barge transportation, however, volume is the limiting factor. Because densified wood can have three times the weight of the same volume of chips, more fuel can be transported per load by rail or barge. Second, densified wood requires roughly one-third as much storage space (cubic volume) as whole tree chips. Third, densification of wood produces a fuel that is similar to coal in combustion and handling characteristics. Densified wood can therefore be substituted almost directly for coal at coal-fired facilities.

Summary

The study reported here was undertaken to determine the economic potential of dead lodgepole pine timber in northeastern Oregon as fuel or other products. This timber represents a major resource on extensive areas in the western United States. Although the harvesting costs determined in this study cannot be applied directly to other situations, the methods used should be useful in assessing the potential of other stands of dead timber.

During the 3 months of experimental logging in 1979, a highly mechanized system of harvesting was used to produce 3,178 tons, ovendry, of whole-tree chips and 1,151 tons, ovendry, (460 thousand board feet) of logs. Harvesting equipment included feller-bunchers, rubber tired skidders, a mobile chipper, a log-limbing and bucking machine, and a mobile log loader. The 197 vanloads of chips were hauled by a contractor to a plant that produces wood fiber insulation board. The logs were hauled to stud mills, house-log manufacturers, or a re-sorting yard where some were chipped. The costs reported for producing whole-tree chips from dead lodgepole pine are considered quite representative for the locality because of the operator's experience. Costs of producing logs are considered less reliable because of his inexperience in log-making and sorting methods and coordinating the production of logs and chips.

On harvest units where both chips and logs were produced, the cost of producing whole-tree chips and delivering the chips 50 miles was $31.30 per ton, wet; $41.07 per ton, ovendry; or $49.30 per bone-dry unit. Where chips only were produced (as on units 46 and 42), the average delivered cost of chips was $35.55 per ton, ovendry. This indicates that optimum coordination of producing logs and chips was not achieved during the 3-month study. Size of trees and condition of the dead lodgepole pine, as represented by the six harvest units, did not justify the expense of operating a limbing and bucking machine. Use of a log-loader to sort and load logs may have been justified but was not tested.

Logs that were produced along with chips on four of the harvest units cost an average of $50.28 per ton, wet, or $60.49 per ton, ovendry, delivered an average distance of 50 miles. The delivery costs ranged from $73.94 per ton, ovendry, on unit 4 to $52.67 on unit 11H. The average cost of $60.49 per ton converts to $151.23 per thousand board feet at 2.5 tons per thousand board feet.

We estimate that if all the material from the six harvest units had been chipped, 4,329 tons of ovendry chips would have been produced. The fuel equivalent per ton of ovendry chips would have been 17.4 million British thermal units, and the energy required to harvest and deliver each ton would have been 0.59 million Btu's, or only 3.4 percent of the energy available in the chips. More significant is the fact that dead lodgepole pine can be burned at an average efficiency of 75 percent, compared to an average efficiency of 65 percent, or less, for most wood fuel now used by industry.

Metric Equivalents

1 ton = 0.9072 tonne
1 acre = 0.4047 hectare
1 cubic foot = 0.0283 cubic meter
1 board foot = approximately .00566 cubic meter, at 5 board feet per cubic foot
1 Btu = 1 056 joules
1 gallon = 3.7853 liters
1 pound = 0.4536 kilogram

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Ince, Peter J.; Henley, John W.; Grantham, John B.; Hunt, Douglas L. Costs of harvesting beetle-killed lodgepole pine in eastern Oregon. Gen. Tech. Rep. PNW-165. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1984.** 26 p.

The cost of harvesting and recovering round wood logs and whole-tree chips from small diameter lodgepole pine (*Pinus contorta*) infested by mountain pine beetle (*Dendroctonus* sp.) was studied in the Blue Mountains of eastern Oregon in 1979. Mechanized harvest operations were conducted on six study sites totaling 134 acres. The average cost of producing chips was $31.30 per ton, wet, delivered 50 miles from harvest sites. The average cost of logs was $50.28 per ton, wet, delivered the same distance. A gross energy balance indicates that energy required by harvesting was about 3.4 percent of the gross energy content of the delivered products.

Keywords: Logging enterprise costs, lodgepole pine (dead), wood utilization, energy, insect damage (-forest products, mountain pine beetle.

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Agriculture

Forest Service

Pacific Northwest
Forest and Range
Experiment Station

General Technical
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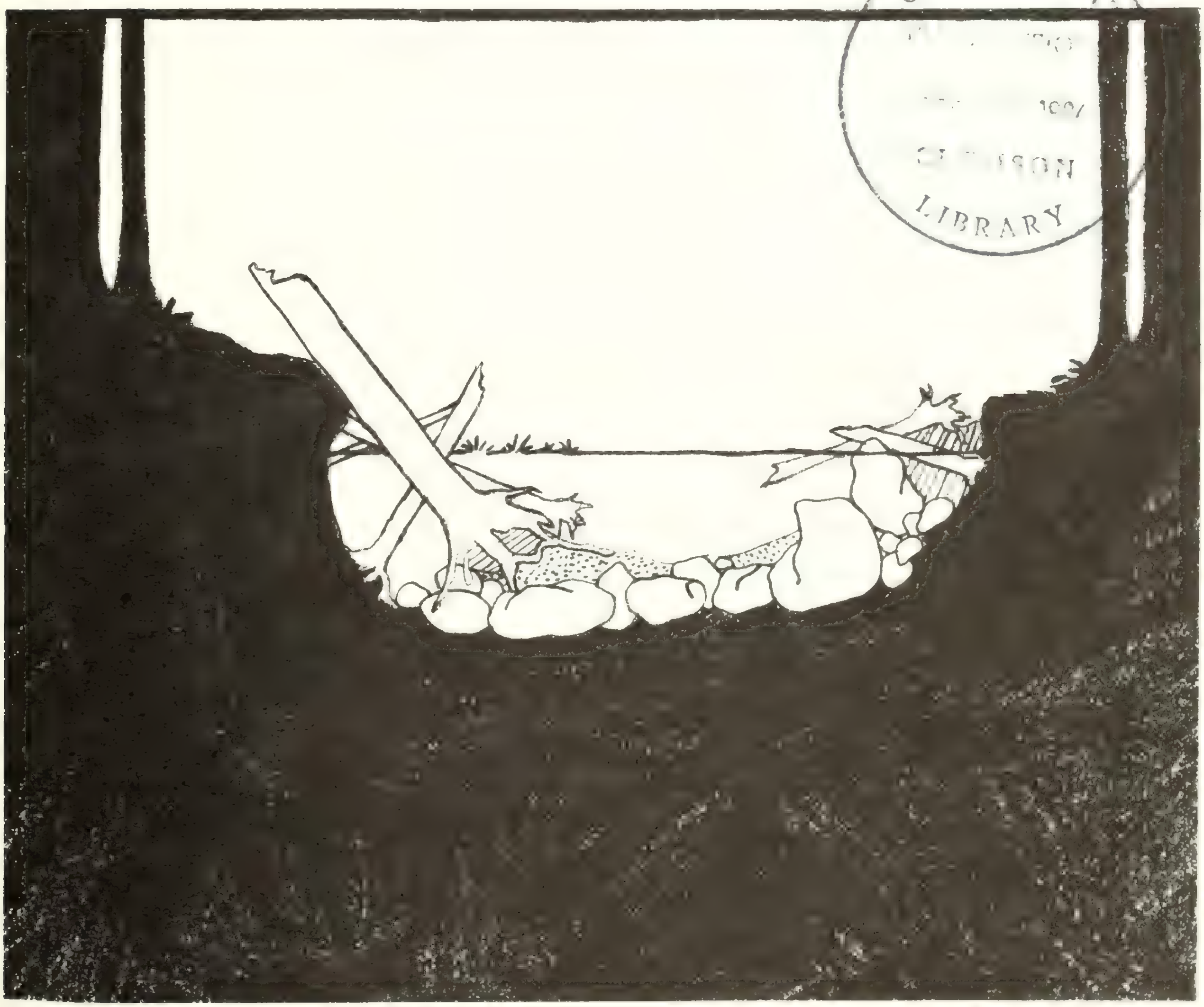
PNW-166

June 1984

Organic Debris in Small Streams, Prince of Wales Island, Southeast Alaska

Frederick J. Swanson, Mason D. Bryant, George W. Lienkaemper, James R. Sedell



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Abstract

Swanson, Frederick J.; Bryant, Mason D.; Lienkaemper, George W.; Sedell, James R. Organic debris in small streams, Prince of Wales Island, southeast Alaska. Gen. Tech. Rep. PNW-166. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1984. 12 p.

Quantities of coarse and fine organic debris in streams flowing through areas clearcut before 1975 are 3 and 6 times greater than quantities in streams sampled in old-growth stands in Tongass National Forest, central Prince of Wales Island, southeast Alaska. The concentration of debris in streams of clearcut Sitka spruce-western hemlock forests in southeast Alaska, however, is about half that in streams of clearcut Douglas-fir-western hemlock forests in western Oregon. Management guidelines for maintaining natural debris conditions include minimizing the addition of fresh material to a channel during management activities, leaving natural accumulations of debris, and managing streamside areas for production of a continuous, long-term supply of large debris for channels. Considerations in planning stream cleanup include the length of time the debris has resided in the channel and the stability of debris, which is a function of its size, orientation, and degree of burial and decay.

Keywords: Stream debris, fluvial processes, fish habitat, watershed management, logging hydrology, (-hydrology, Alaska (southeast), southeast Alaska.

Introduction

Organic debris can greatly influence the physical and biological character of small to intermediate-sized streams flowing through forest land. Forest management practices, therefore, have the potential to alter aquatic ecosystems through changes in the quantity, size, spatial distribution, and configuration of organic debris in and adjacent to streams. Although these generalizations are widely recognized, few studies have quantified relationships among forest practices, stream debris conditions, and their effects on aquatic organisms.

These relationships are being examined by an interdisciplinary research group studying several small streams in the drainages of Staney and Shaheen Creeks within Tongass National Forest on Prince of Wales Island, southeast Alaska (fig. 1). Study sites include both streams in forested areas and streams flowing through 6- to 10-year-old clearcuttings. Objectives of the overall study are to (1) characterize and contrast quantity, stability, and spatial distribution or organic debris in streams flowing through forested and clearcut areas, (2) examine seasonal population dynamics of fish and community structure of invertebrates in small streams, and (3) determine effects of debris removal from streams flowing through clearcuttings on aquatic habitat and organisms. This article summarizes preliminary results of the first objective, characterizing conditions of debris in small streams.

Research on effects of logging on organic debris in streams is sparse. Rothacher (1959), Froehlich (1971), and others point out that floated organic debris aggravates flood damage under natural conditions, and logging and road construction may increase the problem by supplying channels with slash of size classes floatable at high flow. Froehlich (1973) reports debris loading in streams of steep forests in western Oregon and the effects of several falling and yarding practices on debris conditions. He observed increases in debris concentration from 0 to over 400 percent, depending on the type of logging practice employed. Other researchers (Heede 1972a, 1972b;

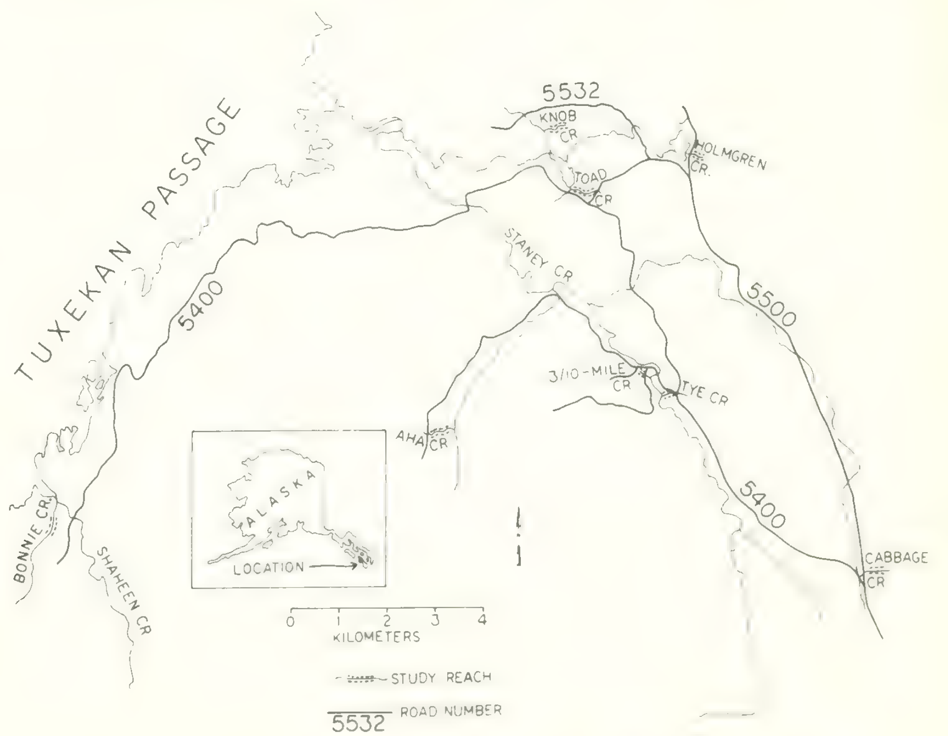

Figure 1.—Location of study streams in central Prince of Wales Island, Alaska.

Study Sites

Swanson and others 1976, Swanson and Lienkaemper 1978; Keller and Talley 1979) have examined organic debris in streams flowing through forest areas and suggest practices to minimize the effect of forest management activities.

Each of these studies recognizes organic debris as an integral part of the natural condition of streams in forested areas. In general, suggested management guidelines emphasize maintaining quantities of debris and size and spatial distributions similar to natural conditions. Establishing these guidelines as a management objective poses special problems when debris loading of a stream was altered some years previously. What are the environmental effects and the economic costs and benefits of various cleanup or rehabilitation options? This paper takes the first step in addressing this question for low-gradient streams in southeast Alaska.

Study sites are located in the drainages of Staney and Shaheen Creeks in the central portion of Prince of Wales Island, southeast Alaska. The landscape has been sculpted by glaciers that cut flat-bottomed, U-shaped valleys and formed broad areas of low relief. Study streams are in valley bottoms in areas of gentle channel gradients (table 1).

Natural, old-growth forests in the study area are dominated by mixed-aged stands of Sitka spruce (*Picea sitchensis*) and western hemlock (*Tsuga heterophylla*) in which some individual trees exceed 400 years in age. Areas were clearcut by free falling and high lead cable yarding systems 6 to 10 years before the study. Slash appears to have accumulated in the shallow depressions of drainages from logs being yarded across a logging unit.

The central portion of Prince of Wales Island has a cool, wet, maritime climate with a mean annual temperature of about 7°C and annual precipitation of about 2500 mm (Barr and Swanston 1970). No gaging records have been kept on any small streams in the area, but streamflow is highly responsive to changes in precipitation and snowmelt in steep valley-wall drainages.

Study streams selected and their sampled reaches are representative of small, low-gradient, fish-bearing streams in the region. Sampling criteria for the fisheries phases of the overall study dominated site selection; the work reported here supports the fisheries study. Characteristics of channel geometry are listed in table 1. The streams in clearcuttings where debris manipulation was planned contained juvenile Coho salmon (*Oncorhynchus kitsutch*), Dolly Varden (*Salvelinus malma*), and cutthroat trout (*Salmo clarki*). A large stream, Bonnie Creek, was also selected for study because (1) it contained natural debris typical of streams its size in the area, (2) logging began in the adjacent stand in summer 1978; resulting changes in debris conditions could be followed, and (3) the site had contiguous, 100-m reaches with relatively high and low concentrations of debris, providing opportunity for comparisons.

All names of small streams are informal.

Table 1--Characteristics of channel geometry at study sites, Prince of Wales Island, Alaska

Creek	Length sampled	Number of transects	Average width[1]	Average gradient
	Meters		Meters	Percent
Aha	300	30	4.8	3
Cabbage	100	11	4.2	7
Holmgren	90	19	2.1	1
3/10-Mile	90	19	3.0	5
Knob:				
Upper	100	11	2.6	2
Lower	100	11	2.8	
Toad:				
Upper	100	11	1.4	7
Lower	100	11	1.9	
Tye:				
Upper	85	9	7.0	4
Lower	85	8	6.0	

[1]Average width of channel at transects.

Methods

Quantities of organic debris were measured using methods developed by Froehlich (Froehlich and others 1972, Lammel 1972, Froehlich 1973). Froehlich drew on methods originally used to sample conditions of forest fuel. Fine debris (less than 10 cm in diameter) was sampled by using line transects crossing the stream; larger wood was sampled by scaling all pieces between successive line transects. Unlike Froehlich, however, we distinguished channel from flood plain. Channel was the area we judged to be wetted during annual high flow and bounded by low banks. Flood plain included streambanks and areas back from the bank less frequently inundated.

Fine woody debris was sampled by three diameter classes (less than 1 cm, 1 to 3 cm, 3 to 10 cm), using a line intersect method along a series of transects crossing the channel at regular intervals (fig. 2). In some cases, 25 percent of a length of transect was sampled in a series of randomly positioned, 30-cm-long segments of the line. The entire line transect was sampled on other streams. We counted all sticks in the three diameter classes that intersected a vertical plane along the sampled portion of the transect. Volume of fine debris per unit area of horizontal surface (V) in each size class was calculated by:

$$V = \frac{\pi^2 n d^2}{8L}$$

where n = number of intersections of all sticks in a diameter class, d = mean diameter of that class, and L = length of transect actually sampled (see Van Wagner 1968 for derivation). For mean diameters of each size class we used values determined by Froehlich and others (1972) in old-growth Douglas-fir (*Pseudotsuga menziesii*)–western hemlock forests in the western Cascade Range, Oregon: 0.423 cm for less-than-1-cm class, 1.792 cm for 1 to 3 cm, 5.049 cm for 3 to 10 cm. Specific weight of organic debris was assumed to be 0.50 g/cm^3 (USDA Forest Service 1974) for calculating mass of organic debris sampled.

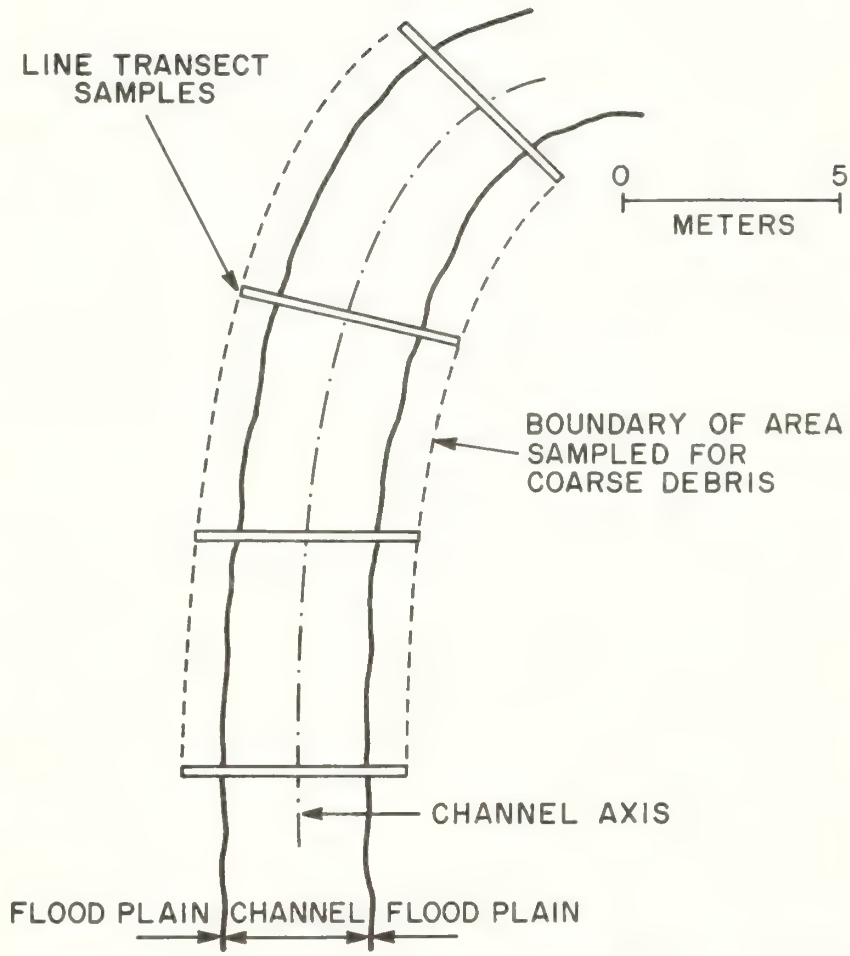

Figure 2.—Line transects and coarse debris sampling plots.

Pieces of coarse organic debris (greater than 10 cm in diameter) were scaled individually by measuring diameters of the large and small ends and length, using calipers and tape. We scaled only portions of debris pieces that fell within a belt bounded by ends of line transects (fig. 2). Coarse debris in and over the channel was segregated into "potential" (material more than 1 m above the streambed) and "effective" debris (within 1 m of the bed). We interpreted effective debris as being capable of influencing streamflow, although in some instances the influence might occur only at very high flow. Potential debris consisted of fallen trees spanning the channel that would eventually collapse into the stream. The volume of each piece of large wood was calculated assuming it to be a section of a cone. Total wood volume was divided by sample area to determine concentration of large wood in terms comparable with data for fine woody debris.

Line transects on Cabbage and Tye Creeks extended 5 m back from the channel edge or until a steep, high (greater than 1 m) bank was encountered. Toad Creek was sampled with a 10-m-long transect centered on the stream. A 5-m length of transect was used on Holmgren, 3/10-Mile, and Knob Creeks. In all cases, line transects were truncated where they encountered steep, high banks.

Results

Means and standard deviations (s) of debris loading and surface area were calculated from measurements of trans-transects for coarse material. Standard errors (S.E.) were determined for each mean:

$$S.E. = \frac{s}{\sqrt{n}}$$

where n = number of transects or intervals (table 1). A standard error of the mean could not be calculated for total effective loading because different sampling methods were used for fine and coarse debris.

The stream reaches flowing through clearcuttings (Tye, Toad, and Knob Creeks) and forested areas (Cabbage and Aha Creeks), were mapped at a scale of 1:120 using tape and compass. Bonnie Creek was mapped at 1:200 with the same methods. Ages of trees growing on gravel bars and large debris at the Bonnie Creek site were determined by counting tree rings in cores taken with an increment borer. Planimeter measurements from the maps of study streams were used to estimate the percent of the stream area in large debris, accumulations of fine debris, and undercut banks—an important component of fish habitat.[1] Channel gradient was measured with a hand-held clinometer.

[1] Unpublished maps on file with Research Work Unit 1653, Forestry Sciences Laboratory, Corvallis, Oregon, and Research Work Unit 1705, Forestry Sciences Laboratory, Juneau, Alaska.

Comparison of Debris From Streams in Clearcuttings and Forested Areas

Concentrations of organic debris in streams flowing through forested areas are significantly lower ($P < 0.010$) than in streams in 6- to 10-year-old clearcuttings (figs. 3 and 4, and tables 2 and 3). Reaches of streams in clearcuttings are dominated by accumulations of fine organic debris (less than 10 cm in diameter), mainly logging slash. Large organic debris in reaches in forested areas

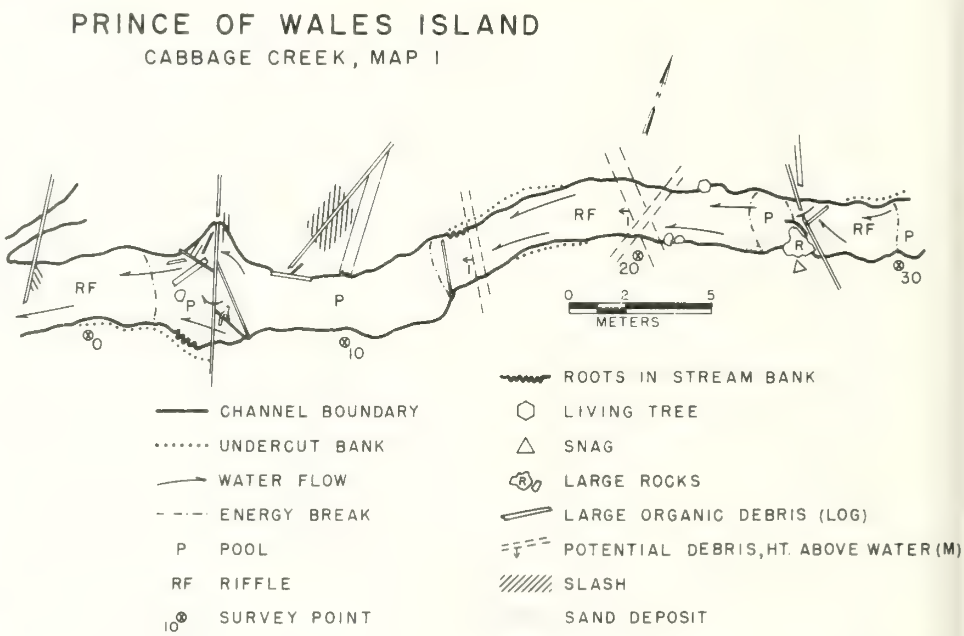

Figure 3.—Organic debris in Cabbage Creek.

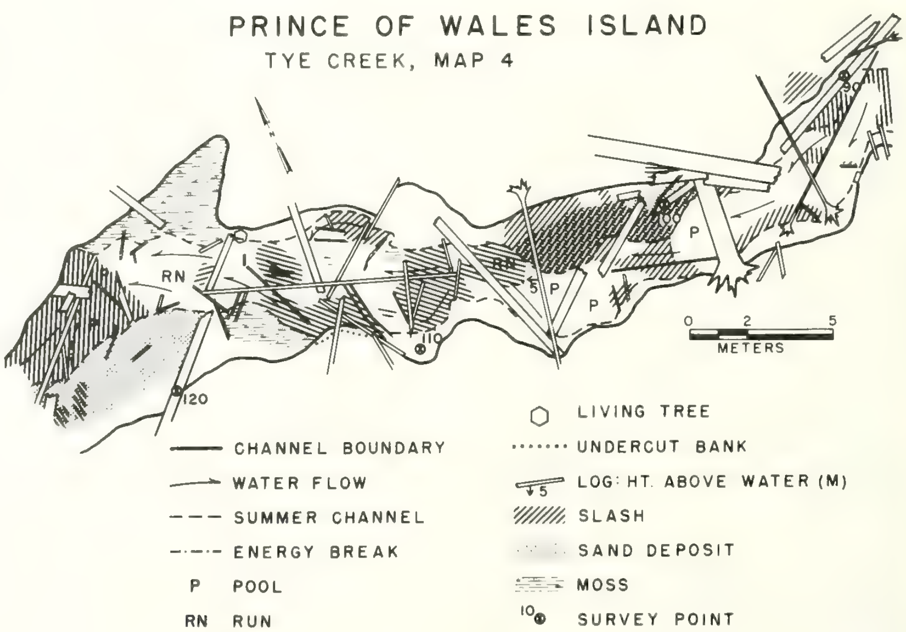

Figure 4.—Organic debris in Tye Creek.

Table 2--Debris loading in sampled reaches of study streams at forested sites, Prince of Wales Island, Alaska[1]

Creek	Area	Fine debris loading	Coarse debris: Potential	Coarse debris: Effective	Total effective loading
	m^2	- - - - - - - - - - - kg/m^2	- - - - - - - - - - -		
Cabbage:					
Channel	225	0.5 ±0.2		2.8 ±0.8	3.3
Flood plain	249	1.0 ±0.4		4.6 ±2.1	5.6
Total	474	0.8	1.3 ±0.5	3.8	4.6
Holmgren:					
Channel	187	2.6 ±0.5		7.1 ±1.5	9.7
Flood plain	263	0.5 ±0.1		4.7 ±1.8	5.2
Total	450	1.4	1.0 ±0.9	5.7	7.1
3/10-Mile:					
Channel	273	1.0 ±0.3		11.7 ±2.6	12.7
Flood plain	176	0.4 ±0.2		5.7 ±1.8	6.1
Total	449	0.8	2.7 ±2.1	9.4	10.2
Aha:					
Channel	1383	0.8 ±0.1		11.4 ±2.3	12.2
Flood plain	646	1.0 ±0.2		12.0 ±3.0	13.0
Total	2029	0.9	2.0 ±0.8	11.6	12.5
Average:					
Channel		1.0		10.1	11.1
Flood plain		0.8		8.4	9.2
Total		0.9	1.9	9.4	10.3

[1]Debris values include mean ± standard error of the mean.

Table 3--Debris loading in sampled reaches of study streams at clearcut sites, Prince of Wales Island, Alaska[1]

Creek	Area	Fine debris loading	Coarse debris: Potential	Coarse debris: Effective	Total effective loading
	m^2	- - - - - - - - - - - kg/m^2	- - - - - - - - - - -		
Tye:					
Channel	626	6.7 ±1.3		27.8 ±9.9	34.5
Flood plain	514	4.1 ±0.8		38.8 ±7.2	42.9
Total	1140	5.5	2.5 ±1.2	32.8	38.3
Toad:					
Channel	420	8.5 ±2.1		53.3 ±13.1	61.8
Flood plain	497	12.3 ±2.2		23.2 ±5.1	35.5
Total	917	10.6	6.6 ±3.2	37.1	47.7
Knob:					
Channel	532	3.6 ±0.5		12.1 ±2.7	15.7
Flood plain	468	2.7 ±0.5		8.4 ±2.0	11.1
Total	1000	3.1	1.4 ±0.8	10.4	13.5
Average:					
Channel		6.1		29.3	35.4
Flood plain		6.4		23.9	30.3
Total		6.2	3.4	26.8	33.0

[1]Debris values include mean ± standard error of the mean.

generally occurs as discrete accumulations composed of a few pieces, whereas accumulations of debris in clearcuttings extend for tens of meters down the length of the channel.

Loading of organic debris in stream reaches in forested areas contrasts markedly with that in the three reaches in clearcuttings (tables 2 and 3). Coarse and fine debris loading in the clearcut areas exceeds that in forested areas by about 3 and 6 times, respectively. Flood plains in clearcutttings have higher debris loading than in forested areas by factors of 3 and 8 times for coarse and fine debris. The quantity of overhanging (potential) large debris appears similar in streams flowing through clearcuttings and forested areas.

Average quantities of coarse and fine debris are quite variable both within and between sites. Concentrations of debris are not systematically different between channels and flood plains areas for either forested or clearcut sites. For the sampled channels in forested areas, fine debris ranges from 0.5 to 2.6 kg/m^2 and coarse debris varies from 2.8 to 11.7 kg/m^2. The magnitude of variation among clearcut study sites appears somewhat less.

The average amount of coarse and fine debris in logged areas appears greater than in unlogged areas, but the differences are difficult to detect statistically because of the small sample size. Because the distribution did not appear to be normal, the Mann-Whitney test was used to test for equality of distribution functions of fine debris, coarse debris, and total effective debris loading between stream reaches at logged and unlogged sites (Conover 1971). The hypothesis of equality of distributions is rejected at $P = 0.10$ ($T_2 = 6.0$, $P = 0.054$) in all three cases. It is important to note, however, that our scope of inference is limited by the very small sample size.

Some types of wood processing by invertebrates and organisms causing decomposition are regulated by surface area of available wood rather than volume of wood. Although much of the

mass or volume of wood in streams is contained in a few large pieces, much of the surface area is in the smallest size classes of debris (tables 4 and 5). Coarse material in channels accounts for 73 to 93 percent of total concentration by weight, but it contributes only 20 to 53 percent of total wood surface area. Within the fine debris category, the less-than-1-cm-diameter class generally contributes as much or more surface area of wood as the 1- to 3- and 3- to 10-cm-diameter classes.

In addition to measuring influence of debris in terms of concentration, we also tallied the number and size of debris accumulations over the length of study reaches. Debris accumulations extending over more than two-thirds of the width of sampled streams in forested areas occurred with a spatial frequency of about 1 per 13 m of channel length (1 per 4 channel widths.)[2] Accumulations extending across less than two-thirds the width of streams in forested areas had an average spacing of 1 per 11 m of channel length (1 per 4 channel widths). Similar determinations in streams flowing through clearcuttings were difficult to make because debris coverage was nearly continuous over long reaches of some channel sections.

[2]Channel width is a measure commonly used by geomorphologists to describe spacing of geomorphic features along stream channels. Pools and riffles, for example, are typically spaced 5 to 7 channel widths apart along the channel length.

Table 4--Summary of debris loading (kg/m^2) and surface area (m^2 of wood surface/m^2 of horizontal surface) by class of debris in four study streams at forested sites, Prince of Wales Island, Alaska[1]

Creek	Fine Debris			Effective coarse debris
	<1 cm	1-3 cm	3-10 cm	>10 cm
Aha:				
Channel--				
Surface area	0.09 ±.02	0.09 ±.02	0.09 ±.02	0.26 ±.05
Loading	0.05 ±.01	0.2 ±.04	0.6 ±.11	11.4 ±2.3
Flood plain--				
Surface area	0.28 ±.12	0.12 ±.03	0.12 ±.04	0.28 ±.07
Loading	0.2 ±.06	0.3 ±.06	0.8 ±.3	12.0 ±3.0
Cabbage:				
Channel--				
Surface area	0.08 ±.02	0.06 ±.03	0.06 ±.03	0.12 ±.03
Loading	0.04 ±.01	0.1 ±.07	0.4 ±.2	2.8 ±0.8
Flood plain--				
Surface area	0.17 ±.02	0.10 ±.03	0.11 ±.06	0.14 ±.06
Loading	0.1 ±.01	0.2 ±.07	0.7 ±0.4	4.6 ±2.1
Holmgren:				
Channel--				
Surface area	0.27 ±.06	0.12 ±.02	0.37 ±.07	0.25 ±.04
Loading	0.2 ±.03	0.3 ±.05	2.4 ±.42	7.1 ±1.5
Flood plain--				
Surface area	0.19 ±.04	0.04 ±.01	0.04 ±.01	0.15 ±.03
Loading	0.1 ±.02	0.1 ±.09	0.3 ±.09	4.7 ±1.8
3/10-Mile:				
Channel--				
Surface area	0.11 ±.03	0.08 ±.02	0.12 ±.04	0.34 ±.06
Loading	0.06 ±.02	0.2 ±.1	0.8 ±.3	11.7 ±2.6
Flood plain--				
Surface area	0.12 ±.02	0.03 ±.01	0.04 ±.02	0.15 ±.06
Loading	0.06 ±.01	0.1 ±.03	0.3 ±.1	5.7 ±1.8

[1]Values include mean ± standard error of the mean.

Table 5--Summary of debris loading (kg/m^2) and surface area (m^2 of wood surface/m^2 of horizontal surface) by class of debris in three study streams at clearcut sites, Prince of Wales Island, Alaska[1]

Creek	Fine Debris <1 cm	Fine Debris 1-3 cm	Fine Debris 3-10 cm	Effective coarse debris >10 cm
Knob:				
Channel--				
Surface area	0.28 ±.05	0.28 ±.04	0.45 ±.07	0.33 ±.05
Loading	0.2 ±.03	0.6 ±0.1	2.9 ±0.5	12.1 ±2.7
Flood plain--				
Surface area	0.22 ±.06	0.19 ±.03	0.35 ±.07	0.22 ±.04
Loading	0.1 ±.03	0.4 ±0.1	2.2 ±0.5	8.4 ±2.0
Toad:				
Channel--				
Surface area	1.37 ±.41	0.56 ±.12	1.05 ±.31	0.88 ±.17
Loading	0.7 ±0.2	1.3 ±0.3	6.6 ±2.0	53.3 ±13.1
Flood plain--				
Surface area	1.43 ±.41	1.04 ±.18	1.46 ±.29	0.56 ±1.0
Loading	0.8 ±0.1	2.3 ±0.4	9.2 ±1.8	23.2 ±5.1
Tye:				
Channel--				
Surface area	0.73 ±.26	0.47 ±.15	0.83 ±.15	0.50 ±.09
Loading	0.4 ±0.1	1.1 ±0.3	5.3 ±0.9	27.8 ±9.9
Flood plain--				
Surface area	0.35 ±.10	0.32 ±.08	0.51 ±.10	0.71 ±.09
Loading	0.2 ±.05	0.7 ±0.2	3.2 ±0.6	38.8 ±7.2

[1]Values include mean ± standard error of the mean.

Organic debris in channels can also be assessed in terms of the cover it provides for fish. We measured the cover formed by fine and coarse organic debris and by overhanging banks in the mapped sections of Cabbage and Aha Creeks in forested areas and Toad and Tye Creeks in clearcuttings. Organic debris, predominantly logging slash, covers a much higher proportion of the channel area in the clearcuttings than does the debris at the forested sites (table 6). Fine organic matter comprises the greatest proportion of cover in clearcut areas.

Undercut banks provide 4.5 times more cover in the streams flowing through forested areas than in the channels in the clearcuttings. Although this comparison is based on only four stream reaches, it follows our general impressions from other field observations. Observed cavities below overhanging banks in study streams were typically about 10 to 50 cm high and of similar depth. Roots of both herbaceous and woody streamside vegetation reinforce the banks. Area of overhanging banks may be reduced by crushing during felling and yarding operations. Aggradation after logging may fill channel margins where cover for fish had been provided by overhanging banks.

Table 6--Percent stream channel cover by large and fine debris and undercut banks in mapped sections of study streams, Prince of Wales Island, Alaska

Creek	Stream channel cover: Large debris	Fine debris	Undercut banks
Forested sites:			
Cabbage	2.7	0.6	5.8
Aha	11	3.1	1.8
Clearcut sites:			
Toad	15	36	0.4
Tye	12	22	1.3

Conditions of Debris in an Intermediate-Sized Stream

Organic debris in intermediate-sized and large streams poses special management problems: during a flood, floating debris can damage structures such as bridges and culverts. To characterize stability of organic debris in general and the effect of debris on channel geometry in an intermediate-sized stream, we examined a 200-m long section (14 channel widths) of Bonnie Creek about 400 m upstream from its confluence with Shaheen Creek.

The Bonnie Creek study site is divided into two reaches; the upstream 100-m section contains only about one-third as much large debris as the downstream 100-m section (table 7). Although the gradients of the two reaches are similar, the downstream section is dominated by debris and has nearly twice the average width of the upstream section. Bank-full width in the downstream section is quite variable, ranging from 9.0 to 32.9 m, whereas width in the upstream reach varies only from 7.8 to 11.9 m. Trees appear to have contributed to irregularity of channel width in two ways. Windthrow and streambank erosion lead to root throw of large Sitka spruce; this widens the channel (fig. 5). Downed, dead debris tends to divert streamflow into banks and multiple channels (fig. 5).

Aquatic habitat in the two reaches contrasts markedly. The upstream reach is primarily a continuous riffle through boulders with very little pool area. The debris-dominated section has numerous pools created by patterns of streamflow controlled by large logs. These logs also provide cover and cause deposition of gravel and sand. Influence of large debris in this section of Bonnie Creek increased stream area of pools. Debris-caused deposition of gravel suitable for spawning does not occur in the open reach.

Table 7--Channel characteristics and concentration of large organic debris in Bonnie Creek, Prince of Wales Island, Alaska

Reach	Average length	Average width	Average gradient	Coarse debris loading: Effective	Coarse debris loading: Potential
	- - - - m	- - - -	Percent	- - - - kg/m^2	- - - -
Upstream	100	9.7	1.5	6.8	3.9
Downstream	100	18.8	2.0	23.6	1.5

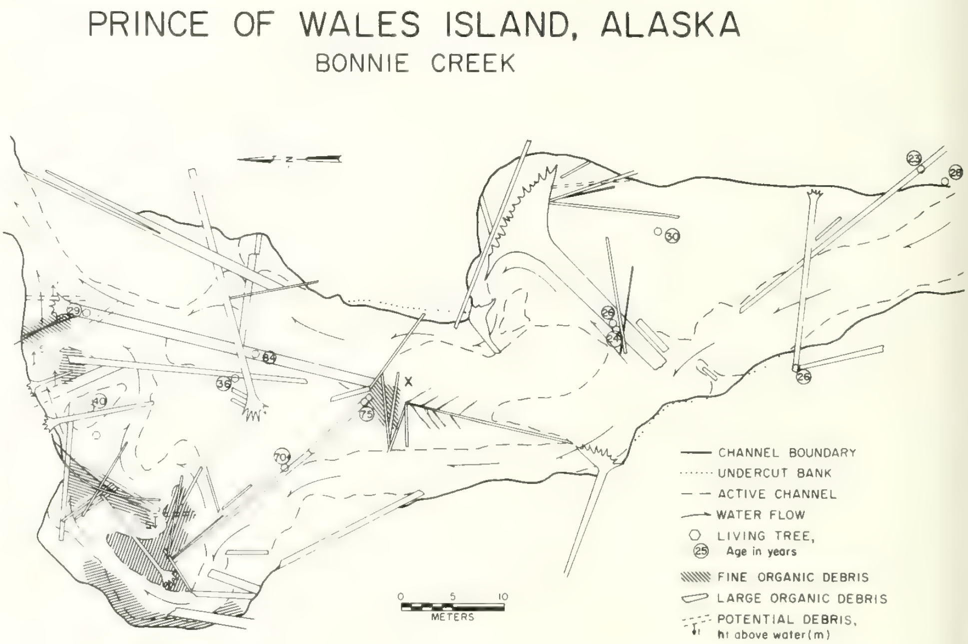

Figure 5.—Organic debris in the downstream reach of Bonnie Creek.

Discussion

The long-term stability and mobility of large organic debris in the study section of Bonnie Creek are indicated by the length of time major pieces of debris reside in the channel and by the size of pieces floated into their present position. Ages of trees growing on downed logs and sediment deposits in the channel (fig. 5) reveal that configurations of the channel and large debris have changed little in the past 20 to 30 years. Major pieces of debris in the northern half of the mapped section have been in place for more than 70 years. Such long times in residence are attributable to slow decay of large pieces of conifer wood, stable orientation in channels, partial burial by fine sediment deposited in slack water set up by the logs, and binding by tree roots growing through pieces of debris and into sediment substrates. Stabilization by partial burial may take several years; substantial root binding may not develop for a decade or more.

The size of large pieces of debris floated onto the head of the split channel section (location marked "X", fig. 5) provides a measure of the size of debris pieces readily floated in this channel. Pieces up to about 8 m long have been floated downstream at high flows. Four logs greater than 4 m in length have accumulated in this pile. This suggests that pieces of debris with lengths up to about half bank-full channel width can be floated through the upstream portion of this reach.

General observations here and elsewhere indicate that pieces with lengths about equal to bank-full width can be transported distances more than several channel widths downstream at high flow (Lienkaemper and Swanson 1980). Longer pieces may have much of their weight supported on ground outside the channel, and they are easily lodged across channels or against trees on banks. Lengths of readily transported pieces may be substantially less than bank-full width where numerous large, stable pieces of debris or rocks break up streamflow and provide sites where floated debris is trapped.

Debris Loading in Streams in Clearcuttings and Forested Areas

The four streams sampled in old-growth forested areas contained an average of 9.4 kg/m^2 of coarse debris and 0.9 kg/m^2 of fine debris. These concentrations of coarse debris are similar to streams sampled in Engelmann spruce -lodgepole pine (*Picea engelmannii-Pinus contorta*) stands in Idaho and spruce-true fir (*Picea* sp.-*Abies* spp.) stands in New Hampshire and Tennessee (Anderson and Sedell 1979). But values of coarse and fine debris loadings in the study streams of forested southeast Alaska are 24 and 30 percent, respectively, of values reported for small streams flowing through old-growth Douglas-fir-western hemlock-western redcedar (*Thuja plicata*) stands in western Oregon (table 8). Concentrations of large debris in streams flowing through coast redwood (*Sequoia sempervirens*) stands are still higher (Keller and Talley 1979; F. J. Swanson, unpublished data). Contrasts in conditions of stream debris in different forest types reflect differences in quantities and size distribution of woody biomass in adjacent forests, rates of wood decay, and successional dynamics of the forest ecosystems supplying large debris to streams. Sitka spruce-western hemlock stands along the southeast Alaska streams, for instance, tend to carry lower biomass than the Douglas-fir— western hemlock forests sampled in western Oregon because the stocking density of large (greater than 60 cm) stems is less in southeast Alaska and the trees are shorter. Trees in the Alaska forest type are also more densely limbed, however, accounting for the higher proportion of fine debris in the southeast Alaska streams.

The apparent magnitude of the effect logging has on the concentration of organic debris in southeast Alaska streams is similar to situations in western Oregon where the same methods of logging and stream protection were employed (table 8). The sampled streams in clearcut areas in southeast Alaska have about three times as much coarse debris and seven times as much fine debris as that measured in streams of forested areas. Froehlich (1973) observed that logging effects in western Oregon depend on the falling methods used and width of buffer strips employed. Highest increases in stream debris were associated with free-falling without buffer strips, the system used at the southeast Alaska study sites. At three western Oregon sites, these harvest methods resulted in about two- and four-fold increases in coarse and fine debris loading, respectively.

Table 8--Organic debris loading (kg/m^2) in sampled reaches of study streams at forested and clearcut sites in western Oregon and southeast Alaska[1]

Condition of stand adjacent to study stream	Number of reaches sampled	Before logging		After logging	
		Coarse[2]	Fine	Coarse[2]	Fine
Western Oregon:[3,4]					
Old-growth forest	10	39.1	3.0		
Clearcut--					
Free-fall	3	24.9	2.6	56.6	11.5
Cable-assisted directional fall	4	50.1	3.8	46.0	12.0
Free-fall with buffer strip	3	38.5	2.5	35.8	3.2
Prince of Wales Island, Alaska:[5]					
Old-growth forest	4	9.2	0.9		
Clearcut, free-fall	3			27.5	6.2

[1]Stream width varied from 1 to 8.5 m.

[2]Diameter of coarse debris = >10 cm.

[3]Bulk density of wood in Oregon streams was assumed to be 0.58 g/cm^3.

[4]Oregon data from Froehlich (1973) and Lienkaemper (unpublished data).

[5]Bulk density of wood in Alaska streams was assumed to be 0.50 g/cm^3.

Differences in loading of large debris between the Alaska and Oregon sites are so great in other respects that even in Alaska streams in clearcut areas, concentrations of coarse debris are about 70 percent the average value of the forested Oregon sites. Concentrations of fine debris after logging at the Alaska sites are about twice the values of forested Oregon sites but much less than concentrations in the seven Oregon stream reaches adjacent to stands logged without buffer strips.

Implications for Management

Implications for management of organic debris in streams can be viewed from a broad range of perspectives—aquatic ecosystems, movement of water and sediment, aesthetics, and others. Effects of organic debris with respect to each perspective are poorly documented, except to say that organic debris is an important component of most streams in natural condition in forested areas.

At present, it is impossible to quantitatively predict the biological or geomorphic consequences of adding, removing, or changing the size distribution of debris in streams. Anderson and Sedell (1979) provide a general conceptual framework linking functional groups of aquatic organisms to debris conditions in streams. This way of viewing the system provides a basis for future efforts to assess biological effects of altered conditions of debris. Current research in western Oregon and in this study has begun to determine the response of the aquatic community to experimentally manipulated debris loading. Research at these sites, and at Hubbard Brook in New Hampshire (Bilby 1979) and in the Redwood Creek basis (Anne MacDonald, University of California at Santa Barbara), is also documenting changes in channel geometry and the storage and transport of sediment following debris removal.

Our meager understanding of effects of altered organic debris conditions leads us to the simple and conservative approach of basing management guidelines on debris conditions typical of streams in natural conditions flowing through forested areas. Debris conditions could also vary in response to natural stand disturbance (Swanson and Lienkaemper 1978). This approach is supported by the growing understanding of the benefits of debris in streams for fish and other aquatic resources. Many workers argue that logging practices should (a) introduce little or no new debris to channels, (b) maintain the natural debris in channels, and (c) manage streamside vegetation as a potential future source of large debris for channels, as well as allowing it to play other ecological roles such as a source of shade and litter (Froehlich 1973, Meehan et al. 1977, Swanson and Lienkaemper 1978, and others). These guidelines pertain to streams and rivers of all sizes.

Debris management poses another set of questions: What debris should be removed from previously disturbed streams and when should it be removed. Again, we must use natural organic debris loading and distributions as a guide. In the debris removal work at small (bank-full width less than 5m), low-gradient streams flowing through clearcuttings on Prince of Wales Island, the following criteria were used for identifying debris to be removed, retained, or added.

1. Remove accumulations of branches, twigs, and needles not buried in sediment.

2. Leave large, stable pieces of debris in quantities and spatial distributions typical of forested reaches. (Stability of pieces is determined by orientation, length of piece relative to stream width, degree of burial by sediment, and stage of decay.)

3. Move large debris into the channel where there are 20-m (5 to 10 channel widths) or longer reaches with no large debris. Place this material in a stable position.

Onsite decisions about what pieces to remove should consider how channel geometry, sediment deposition, and streamside vegetation have responded to existing debris conditions. If debris has been in the channel less than a year or two, channel or sediment systems may still be adjusting to its presence. Debris removal may prolong the period of channel instability. After several years, channel geometry and patterns of sediment deposition adjust to debris conditions. Debris removal in these cases may initiate a new period of instability, particularly if the removed debris is trapped and retained sediment. The rate of this readjustment and sediment release from a cleaned stream reach will depend on a number of factors including history of storms and degree to which root networks have developed in sediment deposits. Deposits in place more than 10 years may be extensively penetrated by fine roots of streamside vegetation. These root systems slow release of sediment from cleaned channel sections and promote stability in the aquatic environment as it adjusts to altered debris loading. Thus, residence time of debris in channels is an important consideration in developing strategies for debris removal.

Providing future sources of large debris for streams is difficult in southeast Alaska, where tree species are shallow rooted and prone to blowdown—especially when the adjacent stand has been removed. Moore (1977) and others offer guidelines for selecting and designing streamside management units (SMU) for maximum effectiveness over both the short and long term. It is important to recognize that some trees in an SMU will fall into the stream years or decades after initial harvest to carry out the important biological and physical roles of large debris in streams. This new debris replenishes residual debris from logging or the previous mature forest—residual debris that is lost from the system by biological and physical breakdown and downstream transport (Keller and Swanson 1979).

Land managers now have difficulty designing SMU's, partly because the composition and structure of natural vegetation along small streams is not often well suited for stream protection once the adjacent stand is removed. This suggests that forest managers should be developing streamside vegetation in managed stands that will provide good SMU's at the end of the present rotation. Strategies for doing so may include (1) coppicing hardwoods by selective pruning so they can be carried through a whole rotation and provide abundant, wind-firm shade early in the next rotation, (2) establishing hardwoods along streams late in a rotation, and (3) thinning around or topping streamside conifers of low commercial value to develop desired, wind-firm crown structure and height. Some of these treatments should be designed to benefit wildlife also. These activities could be carried out as a special phase of standard precommercial and commercial thinning contracts. Exercising such foresight may make tomorrow's SMU's more effective in protecting streams while making sites easier to log and involving the least trade-off in timber volume.

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English Equivalents

1 centimeter (cm) = 0.3937 inch
1 meter (m) = 3.28 feet
1 kilogram (kg) = 2.2046 pounds (avoirdupois)
1 gram (g) = 0.0353 ounces (avoirdupois)
°Celsius (C) = 5/9 (°F -32)

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Quantities of coarse and fine organic debris in streams flowing through areas clearcut before 1975 are 3 and 6 times greater than quantities in streams sampled in old-growth stands in Tongass National Forest, central Prince of Wales Island, southeast Alaska. The concentration of debris in streams of clearcut Sitka spruce-western hemlock forests in southeast Alaska, however, is about half that in streams of clearcut Douglas-fir-western hemlock forests in western Oregon. Management guidelines for maintaining natural debris conditions include minimizing the addition of fresh material to a channel during management activities, leaving natural accumulations of debris, and managing streamside areas for production of a continuous, long-term supply of large debris for channels. Considerations in planning stream cleanup include the length of time the debris has resided in the channel and the stability of debris, which is a function of its size, orientation, and degree of burial and decay.

Keywords: Stream debris, fluvial processes, fish habitat, watershed management, logging hydrology, (-hydrology, Alaska (southeast), southeast Alaska.

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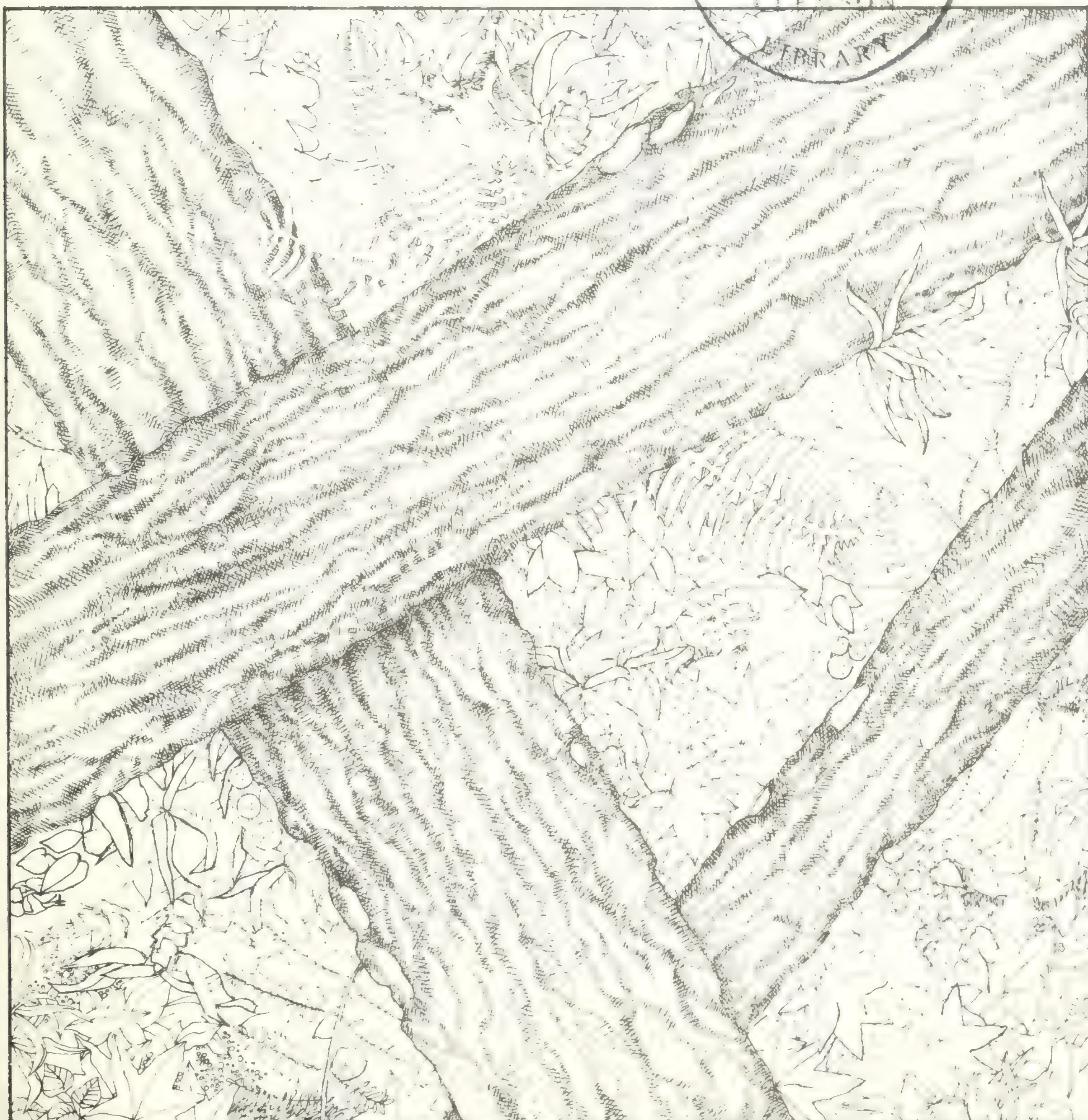
Deterioration Rates of Blowndown Timber and Potential Problems Associated With Product Recovery

Paul E. Aho and James M. Cahill



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Contents

Abstract

Aho, Paul E.; Cahill, James M. Deterioration rates of blowndown timber and potential problems associated with product recovery. Gen. Tech. Rep. PNW-167. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1984. 11 p.

This paper summarizes published reports of deterioration and product recovery studies conducted on dead timber. Decay rates experienced in blowndown timber are presented for western redcedar (*Thuja plicata* Donn ex D. Don), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), and Pacific silver fir (*Abies amabilis* (Dougl.) ex Forbes). Results from product recovery studies conducted on insect-killed western white pine(*Pinus monticola* Dougl. ex D. Don), grand fir (*Abies grandis* (Dougl. ex D. Don) Lindl.), Engelmann spruce (*Picea engelmannii* Parry ex Engelm.), and insect-damaged Douglas-fir are also presented.

Keywords: Blowdowns, decay (wood), deterioration (wood), dead timber, salvage timber, lumber recovery, lumber value.

Summary

The Pacific Northwest periodically experiences catastrophic events that kill large volumes of timber over extensive areas. One such event occurred on May 18, 1980, when Mount St. Helens erupted in southwest Washington, killing an estimated 2 billion board feet of commercial timber. Salvaging dead timber may require several years; hence, resource managers need information on deterioration rates and product recovery to help plan salvage operations. This paper summarizes published results of deterioration and product recovery studies conducted on dead timber.

In general, sapwood of all coniferous species deteriorates at about the same rate and faster than heartwood deterior ates. Second-growth trees and trees with greater sapwood-to-heartwood ratios such as western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and Pacific silver fir (*Abies amabilis* (Dougl.) ex Forbes) deteriorate fastest. The major difference in rate of decay occurs in the heartwood. Heartwood of western hemlock and Pacific silver fir deteriorates fastest, followed by that of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), and then western redcedar (*Thuja plicata* Donn ex D. Don).

Conditions resulting from or existing prior to the eruption of Mount St. Helens may cause deterioration rates to be slower than usual. These conditions include: (1) reduction of fungal inocula, (2) lack of vegetative cover, and (3) high moisture content of the sap during the time of the eruption.

Volume and grade recovery of products manufactured from dead timber can be affected by the presence of sapwood decay, stains, weather checks, and insect borer damage. Timber blown down by the eruption of Mount St. Helens may also suffer from compression failures. The amount of degrade resulting from these defects is influenced by the type of end products to be manufactured from the timber. In general, grading rules used for high quality lumber and veneer are less tolerant of defects than are low quality grades.

Published results of product recovery studies on dead timber have shown that Scribner log scale deductions for weather checks in dead timber can be excessive. Such deductions result in low net scale estimates and create confusion regarding the product potential of dead timber.

Maximum timber volume can be salvaged from recently damaged trees by first cutting small, young-growth trees, then mature hemlock and silver fir, followed by Douglas-fir, and finally, western redcedar. Salvaging high quality, mature stands first may result in greater economic gains than cutting young stands that will decay more rapidly.

Introduction

The May 18, 1980, eruption of Mount St. Helens killed an estimated 2 billion board feet of old-growth and second-growth commercial timber on public and private forest lands in southwestern Washington. Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), Pacific silver fir (*Abies amabilis* (Dougl.) ex Forbes), and western redcedar (*Thuja plicata* Donn ex D. Don) are the major commercial species in the blast-damage area. Large amounts of this timber are thought to be salvageable, but harvesting this resource may be interrupted or prevented for many years by intermittent volcanic activity.

The purpose of this paper is to present decay rates published on blowndown timber for the commercial softwood species in western Oregon and Washington. Also, several product recovery studies conducted on insect-killed timber are reviewed to point out problems associated with utilizing dead timber. Although the information is intended to help resource managers plan salvage operations on Mount St. Helens, it would also be useful when considering windthrow and other catastrophic events that occur periodically in the Pacific Northwest.

Factors Affecting Rate of Decay

Factors that influence the growth and development of wood decay fungi or host-resistance to fungal attack determine the rate of wood decay. These factors have been reviewed by Aho (1974) and will be discussed here. In general, the decay process is regulated by temperature, moisture, oxygen, and environmental conditions that influence these factors.

Wood dried to less than 20-percent moisture content is unsuitable for most decay fungi. Soil type can influence humidity around downed timber and affect its moisture content, particularly when in contact with the ground. For instance, sandy and pumice soils are usually dry on the surface and may have less groundcover that provides shade. Wood in contact with these soils dries quickly, retarding decay. Clay-type soils generally retain moisture and have dense vegetation. Yet increased moisture content of woody material in contact with these soils may reduce the availability of oxygen for fungi, which may also retard decay.

Elevation influences decay of forest residues in several ways. Precipitation—much of it snow—increases with elevation, the sun's rays have a stronger effect at higher elevations, and day and night temperatures are more extreme. In general, temperatures throughout the year at higher elevations are cooler than at lower elevations; thus, there are fewer days at higher elevations when temperatures are optimal for decay. Cartwright and Findlay (1958) found that optimum growing temperatures for most decay fungi ranged between 27 and 33 °C. Where snow remains on the ground until early summer, both temperature and moisture conditions are unfavorable for decay most of the year. On dry, south and west slopes at higher elevations, the stronger effect of the sun promotes rapid drying of the surface and residues, resulting in weathering of exposed wood. Generally, slopes with northwest, north, and northeast aspects are cooler and wetter than others, but their condition may be modified by degree of slope. Steep slopes receive less direct solar insulation, thus surfaces of the soil and residue are cooler and more moist. Steep slopes, however, may be drier, resulting from rapid runoff of surface precipitation and subsurface water. Soils are often thinner, rockier, and thus drier. Russell (1983) noted that deterioration rates were affected by shading and whether or not the trees were uprooted when blown down. He found slower decay rates than expected in western hemlock and Pacific silver fir because trees shaded or not uprooted contained excessive moisture.

Differences in natural resistance to decay has been noted among various tree genera and even among species within a genus. In western Washington, western redcedar deteriorates slowest followed by Douglas-fir, and finally, Pacific silver fir and western hemlock which decay at about the same rate. Regardless of species, sapwood generally decays faster than heartwood. Small logs deteriorate faster than large logs, and top logs faster than logs lower in a tree. This is mainly because large logs and butt logs have smaller ratios of sapwood to heartwood than do small or top logs. Large and butt logs, especially from certain tree species such as Douglas-fir, have thicker bark, which retards drying of the sapwood. The high moisture content slows the decay rate. Small and top logs with thinner bark and greater surface-to-volume ratios dry faster, allowing decay to develop sooner. On dry sites at higher elevations, however, decay of top logs is impeded because they become too dry.

The rate of deterioriation of woody material is closely related to insect activity. Insects serve as vectors of fungi and create infection courts. The general pattern of deterioration begins with attacks by bark beetles and ambrosia beetles, which are vectors of staining and sapwood-destroying fungi. Staining fungi are usually confined to sapwood where they utilize the contents of parenchyma cells in wood rays. Decay fungi rapidly spread through and deterioriate the sapwood. Fungi capable of decaying heartwood, the most damaging being *Fomitopsis pinicola,* then become established. Wood borers, which penetrate deep into logs, may act as vectors of heartwood-rotting fungi and create favorable conditions for rapid spread of decay. Insect activity can also retard the rate of decay. On dry sites, severe bark beetle attacks cause the bark to slough off, resulting in drying and weathering of the exposed sapwood.

Unique conditions resulting from the volcanic blast at Mount St. Helens will undoubtedly influence the rate of deterioration of the killed timber. Because studies have not been previously made under such conditions, we can only speculate how the conditions will affect deterioration. Reduced fungal inocula and insect populations, excessive heat from the blast, deep ash cover, and lack of vegetation cover over the exposed dead timber will all probably slow the deterioration rate.

The time of the year that the damage occurred may also have an important effect on deterioration of the timber blown down by the volcanic eruption. Damage occurred in the spring (May) when sap was flowing in the trees. The moisture content of the sapwood was probably high, high enough to retard decay development at least during the first year after blowdown. This effect may be longer lasting for old-growth trees of all species and for species with thick bark.

Deterioration Rate by Tree Species

Table 1 lists key studies conducted in the Pacific Northwest on deterioration of windthrown or felled Douglas-fir, western hemlock, Pacific silver fir, and western redcedar. This list is a useful index of the literature available on rates of deterioration following blowdown in the Pacific Northwest.

General conclusions drawn from these studies are: (1) some cull or degrade losses will occur almost immediately after trees are windthrown or otherwise felled; (2) deterioration will vary considerably among trees or localities, depending on the immediate environment; (3) sapwood of these conifers deteriorate at about the same rate but more rapidly than heartwood; (4) major differences in the rate of decay occur in the heartwood; and (5) heartwood of western hemlock and Pacific silver fir deteriorate at about the same rate, but more rapidly than Douglas-fir and much more rapidly than western redcedar.

Table 1—Studies conducted on windthrown or felled trees in the Pacific Northwest

Study leader and year results published	Location of areas sampled [1]	Species	Age of trees	Number of trees examined	Number of years since blowdown
Boyce (1929)	Olympic Peninsula, WA	Douglas-fir	Old growth	112	5
		Western hemlock	Old growth	40	5
		Pacific silver fir	Old growth	29	5
		Western redcedar	Old growth	29	5
		Sitka spruce	Old growth	53	5
Buchanan and Englerth (1940)	Olympic Peninsula, WA	Douglas-fir	Old growth	246	5, 8, 15
		Western hemlock	Old growth	183	5, 8
		Pacific silver fir	Old growth	100	5
		Western redcedar	Old growth	49	5
		Sitka spruce	Old growth	254	5, 8, 15
Childs and Clark (1953)	Olympic Peninsula, WA	Douglas-fir	Old growth	68	5½
	Cascade Range, OR	Douglas-fir	Old growth	127	6⅓, 9+
	Olympic Peninsula, WA	Western hemlock	Old growth	46	5½
	Cascade Range, OR	Western hemlock	Old growth	49	6⅓, 9+
	Coast Ranges, OR	Western hemlock	Old growth	66	2½, 5½
	Olympic Peninsula, WA	Pacific silver fir	Old growth	18	5½
	Coast Ranges, OR	Pacific silver fir	Old growth	57	2½, 5½
	Coast Ranges, OR	Sitka spruce	Old growth	89	2½, 5½
Roff and Eades (1959)	Vancouver Island, BC	Western hemlock	Understory	[2]	2, 3, 4
	Queen Charlotte Island, BC	Western hemlock	Understory	[2]	2, 3, 5
	Vancouver Island, BC	Pacific silver fir	Understory	[2]	2, 3, 4
	Queen Charlotte Island, BC	Sitka spruce	Understory	[2]	2, 3, 5
Russell (1983)	Olympic Peninsula, WA	Western hemlock	Old growth	105	2⅔
		Pacific silver fir	Old growth	24	2⅔
Shea and Johnson (1962)	Cascade Range, southwest WA	Douglas-fir	Old growth	[3]	3
	Cascade Range, southwest WA	Douglas-fir	Second growth	[3]	3
	Cascade Range, southwest WA	Western hemlock	Old growth	[3]	3
	Cascade Range, southwest WA	Western hemlock	Young growth	[3]	3
	Cascade Range, southwest WA	Pacific silver fir	Old growth	[3]	3
	Cascade Range, southwest WA	Pacific silver fir	Young growth	[3]	3
Smith, Craig, and Chu (1970)	Vancouver Island, BC	Douglas-fir	Second growth	150	[4] 2, 4, 6

[1] WA = Washington, OR = Oregon, BC = British Columbia.
[2] Study was conducted on pieces of logging slash.
[3] A total of 48 trees were sampled; no breakdown available on species or age class.
[4] Trees were felled and bucked.

Percentages of decay were plotted over tree d.b.h. or log diameter for western redcedar, Douglas-fir, western hemlock, and Pacific silver fir (figs. 1-6). Curves were generated by regression analysis using data published on deterioration of windthrown conifers in western Washington and Oregon (Buchanan and Englerth 1940, Childs and Clark 1953). The two studies included a wide range of environmental conditons and serve to approximate the magnitude of decay in trees killed by the eruption of Mount St. Helens. Tables in the published reports present the average percentage of decay calculated on a cubic-foot basis for each tree d.b.h. or average log diameter class. The number of observations in any d.b.h. or log diameter class was used as a weighting factor in our regressions

Western Redcedar

Sapwood of western redcedar decays as rapidly as sapwood of other tree species, but the decay essentially stops at the heartwood. Figure 1 shows decay had not gone beyond the percentage of sapwood 5 years after windthrow in the Olympic Mountains (Buchanan and Englerth 1940). Although data were not collected after 5 years, the authors noted the heartwood of western redcedar remained sound for decades after windthrow. Childs and Clark (1953) made similar observations.

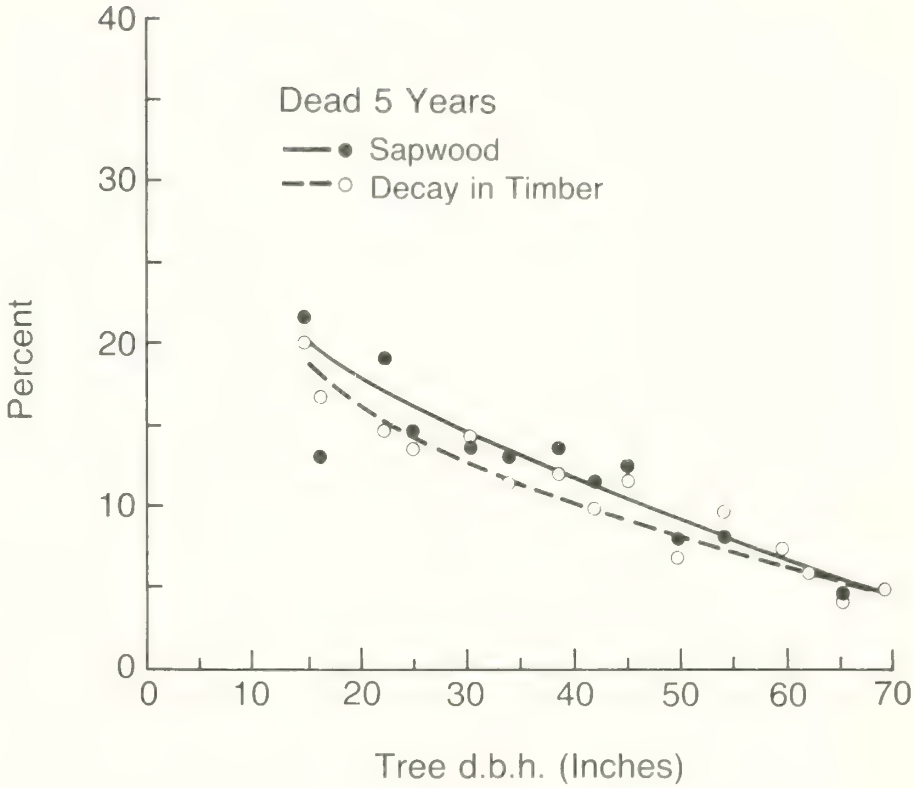

Figure 1.—Percent sapwood and percent decay of windthrown western redcedar plotted through tree d.b.h. (Data from table 7 of Buchanan and Englerth (1940).) Regression equations are:

$$\text{Percent sapwood} = 19.40 - 0.23 \text{ d.b.h.} + \frac{62.2}{\text{d.b.h.}}$$

$$\text{Percent decay} = 13.32 - 0.15 \text{ d.b.h.} + \frac{118.0}{\text{d.b.h.}}$$

Douglas-Fir

Generally, Douglas-fir decays more rapidly than western redcedar because it has a greater percentage of sapwood and the heartwood is less durable. Figures 2 and 3 show the relationship between percentage of decay and log diameter (small-end scaling diameter) for data from Buchanan and Englerth and from Childs and Clark, respectively. These figures show that smaller logs have large amounts of decay 5 years after windthrow and almost complete decay by 15 years. On the other hand, logs greater than 50 inches end diameter remain sound considerably longer, with approximately 25 percent decay after 15 years.

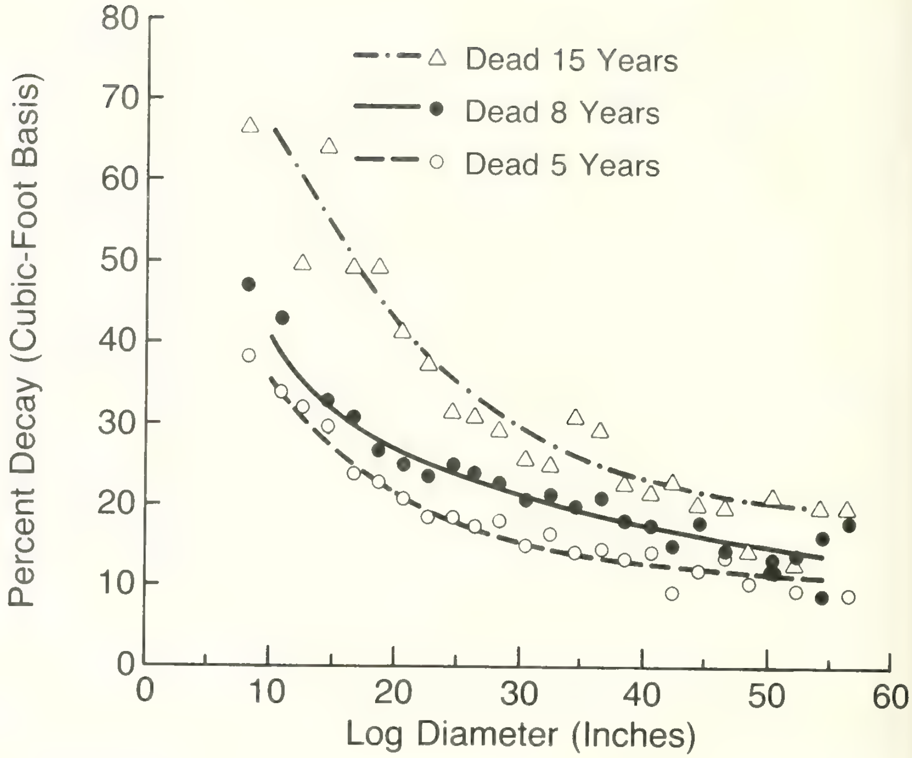

Figure 2. Percent decay of windthrown Douglas-fir plotted through log diameter. (Data from table 2 of Buchanan and Englerth (1940).) Regression equations are:

Dead 5 years: Percent decay $= -6.14 + 0.13d + \frac{600.7}{d} - \frac{2008.6}{d^2}$.

Dead 8 years: Percent decay $= 22.7 - 0.22d + \frac{133.1}{d} + \frac{655.7}{d^2}$;

Dead 15 years: Percent decay $= -22.8 + 0.31d + \frac{1504.5}{d} - \frac{6461.1}{d^2}$.

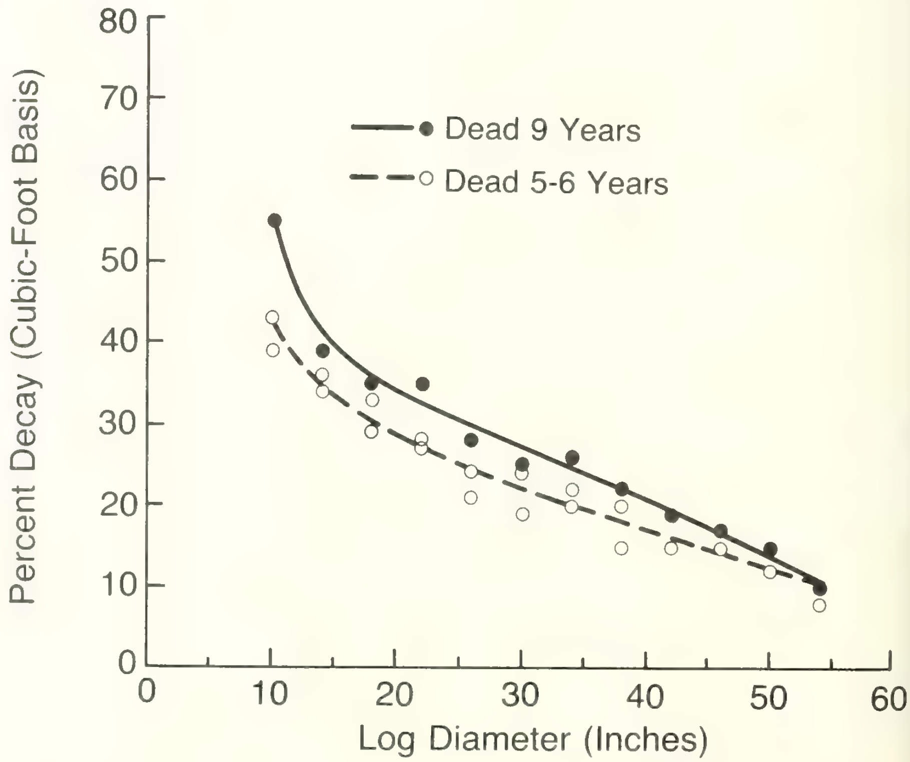

Figure 3.—Percent decay of windthrown Douglas-fir plotted through log diameter (Data from table 2 of Childs and Clark (1953).) Regression equations are:

Dead 5-6 years: Percent decay $= 35.0 - 0.46d - \frac{6.28}{d} + \frac{1266.8}{d^2}$;

Dead 9 years: Percent decay $= 64.5 - 0.83d - \frac{554.6}{d} + \frac{5383.2}{d^2}$.

The percentages of decay for timber dead 5 years were pooled from both studies and regressed over log diameter (fig. 4). The average percentages of decay shown cover a wide range of environmental conditions and represent over 800 logs examined for the presence and extent of sap decay.

Western Hemlock

Western hemlock has more sapwood and less durable heartwood, consequently it decays faster than Douglas-fir or western redcedar. Figure 5 shows the percentage of decay plotted over log diameter for data from Childs and Clark. To illustrate the effect of geographic areas on decay rates, separate curves are shown for each area sampled during their study. The percentage of decay measured on trees dead 5½ years on the Oregon coast (Necanicum area) had almost the same amount of decay as trees dead over 9 years in the Cascade Range of Oregon (Cedar Creek area). Childs and Clark concluded there would be little merchantable volume remaining in even the largest hemlock logs 15 years after windthrow. Buchanan and Englerth reported similar decay rates for western hemlock in the Olympic Mountains of Washington.

Pacific Silver Fir

Pacific silver fir has about the same amount of sapwood and durability as western hemlock, hence the decay rates were similar. Figure 6 is based on data from Childs and Clark and illustrates the difference between sample areas. As with hemlock, percentages of decay for the Necanicum area were high. Only a single curve was fitted to the diameter class averages because the data from Quilcene was limited to logs less than 26 inches end diameter. Average decay 5½ years after windthrow ranged from approximately 80 to 90 percent for 10- to 18-inch logs and from 60 to 65 percent for 38- to 42-inch logs.

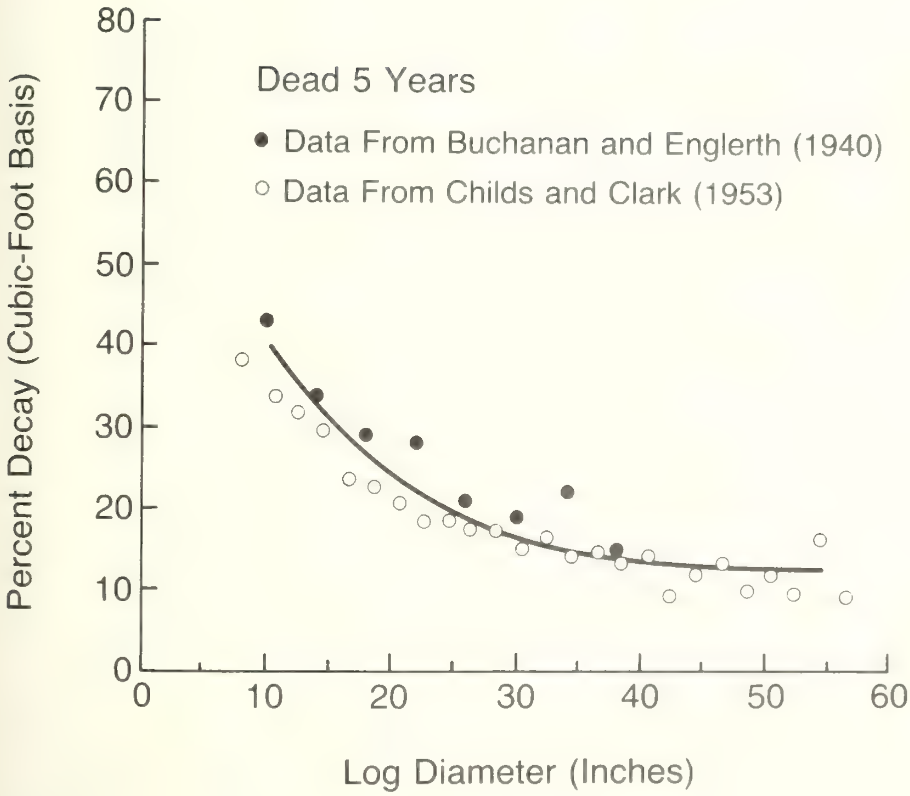

Figure 4.—Percent decay of windthrown Douglas-fir plotted through log diameter (Data is from table 2 of Buchanan and Englerth (1940) and table 2 of Childs and Clark (1953).) Regression equation is:

$$\text{Percent decay} = -21.17 + 0.32d + \frac{974.11}{d} - \frac{3932.7}{d^2}$$

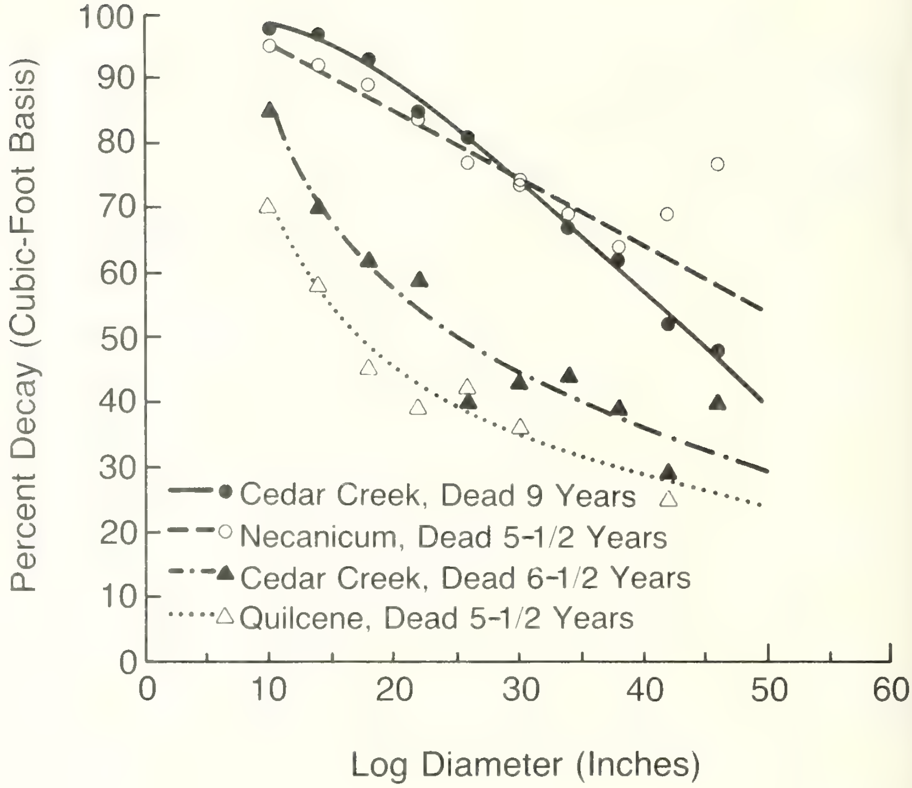

Figure 5.—Percent decay of windthrown western hemlock plotted through log diameter. (Data from table 4 of Childs and Clark (1953).) Regression equations are:

Cedar Creek, dead 9 years: Percent decay $= 136.5 - 1.86d - \frac{195.2}{d}$;

Necanicum, dead 5½ years: Percent decay $= 106.0 - 1.04d$;

Cedar Creek, dead 6½ years: Percent decay $= 42.6 - 0.45d + \frac{473.1}{d}$;

Quilcene, dead 5½ years: Percent decay $= 25.8 - 0.22d + \frac{478.1}{d}$.

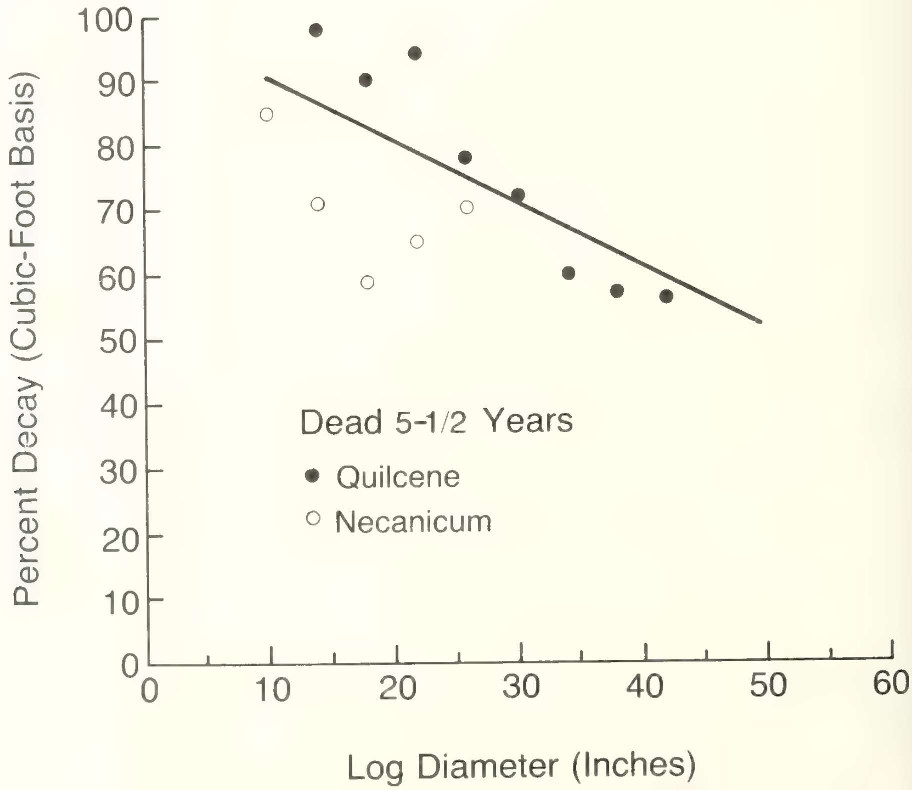

Figure 6.—Percent decay of windthrown Pacific silver fir plotted through log diameter (Data from table 5 of Childs and Clark (1953).) Regression equation is:

Percent decay $= 100.2 - 0.97d$.

Product Recovery From Dead Timber

Defects such as sap decay, stains, weather checks, and holes made by insect borers may cause product degrade and loss in product volume. Results published from several product recovery studies on dead timber follow. Although results of these studies may not be directly applicable to the blowndown timber near Mount St. Helens, a general understanding of the findings should help resource managers minimize losses.

A comparison of log values per gross cubic foot between logs cut from green trees and logs cut from standing dead trees provides an estimate of the magnitude of dollar losses. The values in this case are derived from the actual value of the products manufactured. Table 2 shows the average percent loss in dollars per cubic foot for timber in various conditions.

Table 2—Average percent loss in dollars per cubic foot from dead softwood timber

Species and location	Condition of dead timber	Product manufactured	Percent loss in value
True fir (eastern Oregon)	Dead 0-2 years	2-inch lumber	24
White pine (Idaho)	Dead 0-2 years	1-inch lumber	26
	Dead 3-6 years	1-inch lumber	41
	Dead 7 + years	1-inch lumber	64
Engelmann spruce (Colorado)	Dead 20 + years	2-inch lumber	39
Douglas-fir (Vancouver Island, BC)	Decked 6 months	1- and 2-inch lumber	3
Western hemlock (Vancouver Island, BC)	Decked 6 months	1- and 2-inch lumber	6

Sources: Snellgrove and Fahey (1977), Snellgrove and Cahill (1980), Cahill (1980), and Dobie (1978).

Product Degrade and Volume Loss

Logs processed in a grand fir (*Abies grandis* (Dougl. ex D. Don) Lindl.) study (Snellgrove and Fahey 1977) were cut from Oregon timber killed by tussock moths during an outbreak in the Blue Mountains of Oregon and Washington. There was little sap decay present in the timber; however, weather checks present in the logs showed up as splits in the finished lumber. Splits often cause lumber degrade from Standard-and-Better to Utility and Economy grades. Stains did not contribute to loss in value; there was little stain present in the logs and it is not a grading factor in structural lumber grades.

Lack of stain in the grand fir study contrasts with a white pine (*Pinus monticola* Dougl. ex D. Don) study (Snellgrove and Cahill 1980) in which blue stain was a major factor in loss of value. White pine trees killed by a combination of blister rust and mountain pine beetles were processed in a mill producing Shop and Board items. In these products, for which appearance is important, stains caused the lumber to drop from the Shop, 1 & 2 Common grades to 3, 4, and 5 Common. The 64-percent loss in the older dead pine shows the combined effect of stain, checking, sap decay, and damage from insect borers.

An Engelmann spruce (*Picea engelmannii* Parry ex Engelm.) study (Cahill 1980) was conducted on trees killed over 20 years ago by an epidemic of the Engelmann spruce beetle in western Colorado. The 39-percent loss in the value of dead spruce was largely the result of weather checks. The harsh climate of the Colorado Rocky Mountains tended to reduce the incidence of sap decay in the logs but caused severe weather checking.

A recovery study conducted by Dobie (1978) examined dollar loss in high quality Douglas-fir and western hemlock from Vancouver Island, B.C., caused by the presence of ambrosia beetles. Ambrosia beetles burrow into the sapwood of downed logs, causing small pinholes that degrade Select and Shop lumber items. His data showed that moderate amounts of beetle attacks (15 to 50 holes per square foot) caused C Clear and Better lumber to drop to D Clear, resulting in a 3- and 6-percent loss in value for Douglas-fir and western hemlock, respectively.

Scaling Problems

A problem common to all utilization studies of dead timber results from estimating net Scribner scale for dead logs. Previous studies (Snellgrove and Cahill 1980, Cahill 1980) have shown that Scribner deductions for weather checks are excessive. Many dead logs containing weather checks are considered culls by Scribner scaling rules, yet they recover substantial amounts of lumber. This causes erroneous estimates in overrun and increases the difficulty of appraising dead timber.

Alternative measures of net scale, such as "net equivalents" (Commons 1978), have been used by the USDA Forest Service in some areas to help reduce appraisal problems.

Setting Priorities for Salvage Operations

Other Utilization Problems

An additional problem in utilization may result from the presence of compression failures, sometimes known as timber breaks, which are caused by the compression of wood fibers during extreme flexure. Compression failures show up as thin lines in lumber and severely weaken structural lumber. Structural lumber with compression failures can be downgraded to Utility and Economy grades. This defect has little or no effect on the Select, Shop, and Board grades if the appearance of the piece is not impaired. The extent of this problem in the blowdown timber near Mount St. Helens is not known, but historical evidence from windstorms suggests an increase in the occurrence of timber breaks.

Snellgrove and others (1982) found the volume lost to breakage in the blast zone of Mount St. Helens was typical of that found in normal clearcutting operations, but that log segments shorter than used in normal industrial practices might be more frequent, especially on steep terrain. Shorter segments could be a problem at a stud or veneer mill where losses would occur when cutting to multiples of 8 feet.

The presence of ash and dirt in crevices and checks in Mount St. Helens timber may cause increased wear on saws. Initial concerns about rocks and ash penetrating the wood were unfounded (Snellgrove and others 1982). An analysis made by the Forest Products Laboratory on several wood specimens cut from downed logs supported on-the-ground observations of Snellgrove and others (1982).

Catastrophic events, such as the May 18, 1980, eruption of Mount St. Helens, that kill timber over extensive areas create many problems for resource managers. One immediate concern is the planning of salvage operations that usually span several years. The following points, taken from our review of deterioration and product recovery studies, should help resource managers set logging priorities that will maximize the value of damaged timber.

Age and Species of Timber

Young-growth timber contains a greater percentage of sapwood than old-growth and, hence, will deteriorate faster. This is common knowledge in the timber industry and is well documented in the literature. Past research shows that western hemlock, and Pacific silver fir deteriorate fastest, followed by Douglas-fir, then western redcedar.

Geographic Location

The rate of decay can vary depending on the immediate environment around the dead timber. Soil type, elevation, aspect, temperature, precipitation, insect activity, and the amount of shading can affect the rate of decay in dead timber. As a general rule, Wright and others (1967) found that decay of beetle-killed Douglas-fir was greater in the Cascade Mountains of Oregon and Washington than in the Coast Ranges. They also noted the rate of decay in the southern part of the Douglas-fir subregion was greater than in the north.

End Products

It is important for the resource manager to recognize that dollar losses in lumber and veneer manufactured from dead timber is caused by a combination of product degrade and loss in product volume. Both factors can be important if the salvage area contains old-growth and young-growth timber. Ambrosia beetles can infest dead timber within 2-3 years after blowdown, causing degrade of the high-valued outer portion of old-growth logs. Beetle damage in young-growth timber does not cause the same magnitude of degrade because the primary products are structural grades of lumber and veneer.

Putting these facts together to form rigid recommendations for salvaging dead timber would be a mistake. Each salvage operation has a variety of economic, biological, and practical considerations that make each situation unique. This compilation of key findings from the literature should help provide resource managers with the information needed to set logging priorities that fit their own situation.

Metric Equivalents

1 inch = 2.54 centimeters
1 foot = 0.304 8 meter
1 cubic foot = 0.028 32 cubic meter
5/9(°F-32) = °C

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Aho, Paul E.; Cahill, James M. Deterioration rates of blowndown timber and potential problems associated with product recovery. Gen. Tech. Rep. PNW-167. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1984. 11 p.

This paper summarizes published reports of deterioration and product recovery studies conducted on dead timber. Decay rates experienced in blowndown timber are presented for western redcedar (*Thuja plicata* Donn ex D. Don), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), and Pacific silver fir (*Abies amabilis* (Dougl.) ex Forbes). Results from product recovery studies conducted on insect-killed western white pine(*Pinus monticola* Dougl. ex D. Don), grand fir (*Abies grandis* (Dougl. ex D. Don) Lindl.), Engelmann spruce (*Picea engelmannii* Parry ex Engelm.), and insect-damaged Douglas-fir are also presented.

Keywords: Blowdowns, decay (wood), deterioration (wood), dead timber, salvage timber, lumber recovery, lumber value.

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Forest Service

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Relationships Between Sitka Black-Tailed Deer and Their Habitat

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Abstract

Hanley, Thomas A. Relationships between Sitka black-tailed deer and their habitat. Gen. Tech. Rep. PNW-168. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1984.** 21 p.

Old-growth, western hemlock-Sitka spruce forest in southeastern Alaska is an important element of the habitat of Sitka black-tailed deer. The conversion of uneven-aged, old-growth forests to even-aged, second-growth forests has generated concern about the future carrying capacity of the habitat for deer, especially where snow accumulation is common on winter ranges. Even-aged, second-growth forests produce very little forage for black-tailed deer. Young (<20 years), open stands produce greater amounts of forage than do old-growth stands. Snow accumulates to greater depths in openings than in forest, however, and forage becomes unavailable to deer as it is buried in snow. Habitat quality for Sitka black-tailed deer must be viewed as an energy benefit-cost relation. Energy intake decreases and energy expenditure increases as snow depth increases. Habitats differ in their canopy characteristics and in the amount and kind of forage they produce. The relative qualities of habitats shift with changing snow conditions. An understanding of these dynamic relationships between deer and their habitat is essential for developing management objectives for deer habitat. The current theory is largely qualitative and lacks the ability to yield unambiguous, quantitative predictions. Research is needed to quantify the key relationships between forest canopy and understory production and snow interception, and between the metabolic requirements of deer and the nutritional quality of available forage.

Keywords: Wildlife habitat management, wildlife habitat, timber management, habitat selection, deer (black-tailed), Alaska (southeast).

Contents

Introduction

Sitka black-tailed deer (*Odocoileus hemionus sitkensis*) are endemic to the north Pacific coast from about latitude 53° to 58° N. (Queen Charlotte Sound, British Columbia, to Icy Strait, Alaska), and occupy all of the Alexander Archipelago and a narrow strip of adjacent mainland (fig. 1). Populations have also been established on the Queen Charlotte Islands, the Yakutat area, the islands of Prince William Sound, and Afognak and Kodiak Islands (Wallmo 1981).

Deer harvests in Alaska are small (about 3,000 to 14,000 annually, Johnson and Wood 1979) compared to those in most other western states, but large enough to make deer a major game species in Alaska. Deer densities on winter ranges have been estimated as high as 25 to 75 deer per square kilometer [1] (Barrett 1979). Experienced observers believe, however, that the populations are subject to large fluctuations. Generally, declines are related to attrition from starvation during winters with deep snow and increases are related to successive open winters in which snow does not excessively restrict their range (Klein and Olson 1960, Merriam 1968, Olson 1979, Reynolds 1979, Smith 1979).

Sitka black-tailed deer inhabit the most northwestern extension of the range of mule and black-tailed deer (Wallmo 1981). This is a region of coastal coniferous rain forest. The maritime influence moderates temperatures, but levels of precipitation are high the year around. Historically, fires have been infrequent, and windthrow has been the major disturbance to forests (Harris and Farr 1974). The region is characterized by uneven-aged, old-growth forest with alpine vegetation and icefields at higher elevations (commonly down to 400 m). Although temperatures are mild, compared to continental climates, the habitat of Sitka black-tailed deer has much deeper snow for longer periods than the habitat of their counterpart to the south, Columbian black-tailed deer.

Figure 1.—Present distribution of Sitka black-tailed deer.

The ability of deer to survive inclement winters is influenced by their nutritional condition, the duration of forage restriction, and the amount of forage available at the end of the winter. Although subalpine habitat constitutes an important part of the summer range, the winter range is restricted to forested habitats. As snow accumulates, deer become concentrated on winter range. Management practices that alter the quality of winter range for deer have greater consequences than might be inferred from the acreages affected. This is especially true if the higher quality patches of winter range are affected.

Because logging has increased in southeastern Alaska during the past 30 years, an increasing percentage of the deer habitat will be in even-aged forest in the future. The effect of timber harvesting and stand improvement practices on the quality of habitat for deer is a major concern.

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[1] Schoen, J. W. and Wallmo, O. C., unpublished data on file at Game Division, Alaska Department of Fish and Game, 230 S. Franklin St., Juneau, AK 99801.

Ecological Bases of Deer-Habitat Relationships

Nutrition and Diet

Energy.—The relationships between deer and their habitat are based on seasonal changes in the availability and quality of food, combined with the physiological requirements of deer. During summer, both the quantity and quality of forage are relatively high, and deer gain weight (table 1). During winter, however, both the quantity and quality of forage are low, and deer lose weight. Even in the absence of snow, deer must catabolize body reserves, principally fat and muscle tissue (Bandy and others 1970). The amount and duration of snow accumulation on the ground, however, is of critical importance to the survival of deer in winter. As snow buries forage, the quality of diet decreases along with the intake of dry matter, and energy intake decreases (table 1). At the same time, deer must spend more energy moving around as they sink deeper into snow (fig. 2).

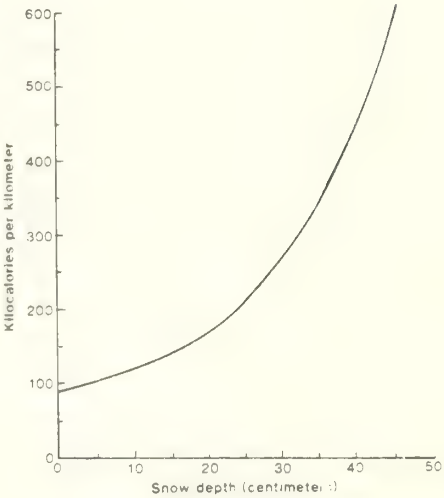

Figure 2.—Energy costs of locomotion through snow for a 40-kg deer (Source: Mattfeld 1974).

Male and female deer use energy in different ways, which is illustrated by their annual fat cycles (fig. 3). Although both males and females gain weight over the summer and lose it during the winter, the seasonal gains and losses occur earlier for males. Because of substantial weight losses during the rut in late fall, males generally begin the winter with lower fat and nutrient reserves than females (Anderson and others 1972, Fowler and others 1967, Nordan and others 1968). Adult males are especially active during the rut and spend little time foraging (Geist 1981, Nordan and others 1968). Late summer and fall is the time when females gain the most (Anderson and others 1972, Mitchell and others 1976). Forage quality and quantity are still relatively high, reproductive demands are relaxed, and energy and nutrient intake generally exceeds maintenance requirements (Short 1975). High costs of gestation and lactation (fig. 4) usually preclude weight gain by reproductive females during spring and summer, although forage quality and quantity are at their peaks then.

Table 1—Estimated daily intake of forage and energy required for maintenance of an adult black-tailed deer in summer and winter

Season	Body weight 1/	AMR 2/	Dry matter intake per kilogram$^{0.75}$ of body weight 3/	Dry matter digestibility 4/	Energy intake 5/	Net energy gain (+) or loss (-)
	Kilograms	Kilocalories	Grams	Percent	- - -Kilocalories- - -	
Summer	45	2,432	80	70	3,722	+1,290
Winter:						
Without snow	50	2,632	59	55	2,334	-298
With snow	50	2,632	48	35	1,208	-1,424

1/ Body weight for 2-yr-old doe in early summer and early winter (source: Bandy and others 1970).

2/ AMR = activity metabolic rate = c (BMR), where c is a constant that varies with seasonal activity levels, and BMR is basal metabolic rate or approximately 70 times body weight to the 0.75 power. BMR also varies seasonally. (sources: Moen 1973, Wallmo and others 1977).

3/ Ovendry weight of forage consumed per kg$^{0.75}$ body weight per day (sources: Alldredge and others 1974, Bandy and others 1970). Intake is lower during winter with or without snow.

4/ Sources: Rochelle 1980, Short 1981, Wallmo and others 1977.

5/ Energy Intake = GE de me (DMI), where GE is the gross energy content (4.5 kcal g^{-1}), de is dry matter digestibility, me is the metabolizable energy coefficient (0.85), and DMI is dry matter intake.

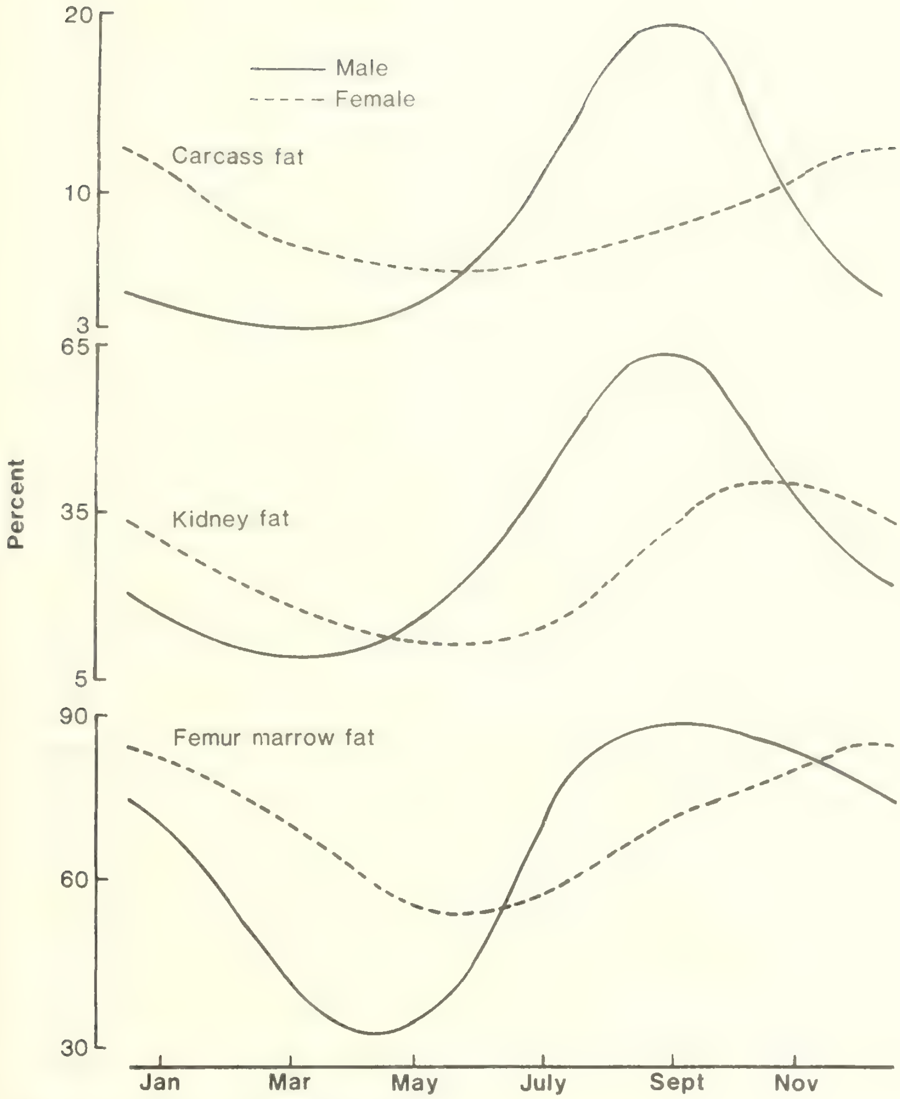

Figure 3.—Annual cycle of fat storage and depletion in mule deer (Source: Anderson and others 1972).

Reproductive costs for pregnant females are insignificant during the most severe conditions of winter. As gestation progresses through spring, however, the availability of nutritious forage is critical for successful reproduction.

Plant nutrients and secondary compounds.—Although deer have specific mineral requirements, deer-habitat relationships are understood best in terms of energy and nitrogen metabolism (Moen 1973). Energy is needed to fuel the deer, while nitrogen is needed to build body tissue. The cell-soluble portion of the forage contains most of the nitrogen and mineral nutrients, as well as readily digestible sugars, starches, and fats; the cell-wall fraction is mainly an energy source (Van Soest 1967). For black-tailed deer with a feeding strategy that emphasizes the cell-soluble fraction (Hanley 1980), nitrogen, mineral nutrients, and energy sources are closely related dietary constituents. Diets that are high in digestible energy also tend to be high in nitrogen and essential minerals as well. The microflora in the rumen synthesizes B-complex vitamins, and vitamin deficiencies appear to be rare (Short 1981).

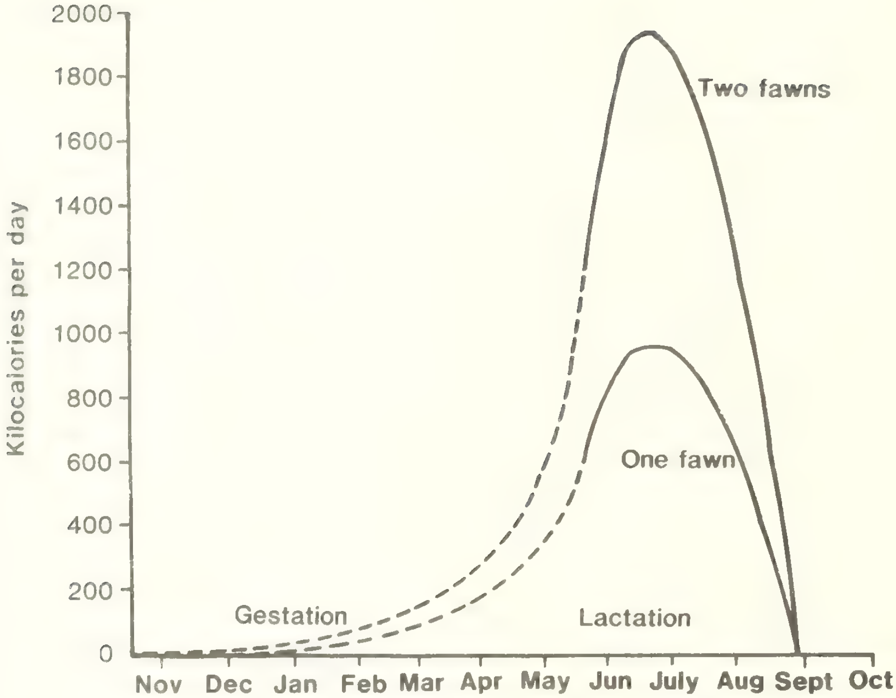

Figure 4.—Energy required for gestation and lactation by a doe with one or two fawns (Source: Moen 1973, Robbins and Moen 1975).

Plants also contain compounds that are deleterious to deer. Many such compounds have been considered secondary by-products of plant metabolism, but more recently their effects have been viewed as "anti-herbivore defense mechanisms" (Feeny 1976, Levin 1976, Rhoades and Cates 1976). Plant secondary compounds are basically of two kinds: (1) toxins and (2) digestibility-reducing substances. While most plants employ both kinds of compounds, one or the other usually predominates in certain types of tissue. Toxins tend to be very specific and dose-dependent, so their effects can be reduced or avoided by herbivores that consume a mixed-species diet. Digestibility-reducing compounds are more general and not dose-dependent, so their effects may be more difficult for herbivores to overcome. Digestibility-reducing compounds commonly interfere directly with nitrogen availability by forming indigestible complexes with proteins and enzymes (Feeny 1975, Mould and Robbins 1981), thus reducing the available nitrogen below the level indicated by the actual nitrogen content of the forage.

The content of secondary compounds varies with species and among individuals within species, and deer may select among them accordingly (Dimock and others 1976, Radwan 1972, Radwan and Crouch 1974). When deer are selective for this or other reasons, the amount of forage available is less than the current annual growth of the plants. Although maximizing energy intake may be a dietary goal, constraints are imposed by the deer's minimum requirements for nutrients and maximum tolerance of secondary compounds. Because chemical composition differs greatly among species, forage variety and a mixed diet are very important to deer (Carpenter and others 1979, Freeland and Janzen 1974, Milchunas and others 1978, Mould and Robbins 1981, Westoby 1974).

Diet composition.—A list of plant species known to be eaten by Sitka black-tailed deer can be obtained from the literature (table 2). Food selection has been reviewed recently by Crouch (1979), Taber and Hanley (1979), and Pierce (1981). Lists of species eaten, however, provide little information about diet selection and the relative importance of constituents. Of greater value is an understanding of the forage characteristics most valuable to deer (Hanley 1982a). The potential quality of forage is based on the relative content of cell solubles and cell-wall materials (table 3).

Although limited, data from southeastern Alaska (table 4) indicate that forages are similar chemically to those in western Washington (Hanley 1980) and Vancouver Island, British Columbia (Rochelle 1980). During the growing season, growing plant tissue (especially shrub leaves and forbs) contains the greatest proportion of cell solubles and nitrogen and is the most valuable deer forage. Plants growing in subalpine and alpine habitats are especially nutritious during summer (Klein 1965). During winter, evergreen shrubs and forbs (for example, bunchberry dogwood, five-leaved bramble, goldthread, foamflower, and pyrola) are the most valuable (Schoen and Wallmo 1979). Although deer eat deciduous shrubs and conifer foliage, herb-layer forages, if available, comprise the major portion of their diet (table 5). Where available, arboreal lichens (for example, beard lichen and alectoria) are readily eaten. They are a valuable energy source and may increase the digestibility of other forages (Rochelle 1980).

Table 2—Plant species reported to have been eaten by Sitka black-tailed deer

Species	Source
Forbs:	
Aruncus sylvester	Pierce 1981
Caltha biflora	Klein 1963
Caltha palustris	Pierce 1981
Coptis aspleniifolia	Merriam 1970, Reynolds 1979
Coptis trifolia	Merriam 1970
Epilobium angustifolium	Merriam 1965, 1968; Pierce 1981
Fauria crista-galli	Klein 1963, Merriam 1971a, Pierce 1981
Heracleum lanatum	Merriam 1964
Listera spp.	Klein 1965
Lysichiton americanum	Klein 1963, Merriam 1971a, Pierce 1981
Maianthemum dilatatum	Merriam 1965, 1967; Reynolds 1979
Potentilla spp.	Pierce 1981
Streptopus spp.	Merriam 1965
Tiarella trifoliata	Merriam 1965, 1967; Reynolds 1979
Vicia gigantea	Pierce 1981
Viratrum viride	Merriam 1965
Ferns:	
Athyrium filix-femina	Smith 1979
Blechnum spicant	Pierce 1981
Dryopteris spp.	Merriam 1965, 1967
Polystichum munitum	Klein 1963
Pteridium aquilinum	Pierce 1981
Thelypteris limbosperma	Pierce 1981
Graminoids:	
Calamagrostis spp.	Merriam 1964
Carex spp.	Klein 1963
Deschampsia spp.	Merriam 1964
Elymus arenarius	Olson 1952
Unspecified species	Merriam 1968, Pierce 1981
Half-shrubs:	
Cornus canadensis	Merriam 1965, 1967, 1970, and 1971a; Pierce 1981; Reynolds 1979
Empetrum nigrum	Pierce 1981
Empetrum spp.	Merriam 1968
Loiseleuria procumbens	Pierce 1981
Oxycoccus microcarpus	Smith 1979
Rubus pedatus	Merriam 1965, 1967, 1970; Reynolds 1979
Vaccinium uliginosum	Klein 1963
Shrubs:	
Arctostaphylos uva-ursi	Merriam 1968
Betula spp.	Smith 1979
Cladothamnus pyrolaeflorus	Pierce 1981
Gaultheria shallon	Pierce 1981
Menziesia ferruginea	Klein 1957b, Pierce 1981
Oplopanax horridum	Klein 1963
Ribes spp.	Pierce 1981
Rosa nutkana	Merriam 1964
Rubus spectabilis	Merriam 1964
Rubus spp.	Pierce 1981
Salix spp.	Merriam 1968
Sambucus racemosa	Klein 1963, Merriam 1964, Pierce 1981
Vaccinium spp.	Klein 1957a, 1957b, 1963; Merriam 1965, 1967, 1968, 1970, 1971a, 1971b; Merriam and Batchelor 1963, Olson 1952, Olson and Klein 1959; Pierce 1981
Viburnum edule	Smith 1979, Pierce 1981
Trees:	
Alnus spp.	Merriam 1968
Chamaecyparis nootkatensis	Pierce 1981
Picea sitchensis	Klein 1963, Merriam 1968
Pinus contorta	Pierce 1981
Thuja plicata	Pierce 1981
Tsuga heterophylla	Klein 1963, Merriam 1965, Olson 1952, Pierce 1981
Tsuga mertensiana	Klein 1957b
Lichens:	
Unspecified species	Pierce 1981, Smith 1979
Mosses and Liverworts	
Unspecified species	Pierce 1981
Algae:	
Fucus spp.	Olson 1952

Table 3—Cell wall composition and estimated digestibility of some major classes of deer forage[1]

Food	Cell solubles	Cell wall	Holocellulose	Lignin	Estimated digestibility	
			Percent dry weight			
					A 2/	B 3/
Grasses:						
Immature	63	37	33	4	87	94
Mature	15	85	70	15	56	20
Forbs:						
Immature	56	44	33	11	71	69
Mature	25	75	57	18	53	27
Woody twigs:						
Immature	64	36	24	12	73	75
Mature	38	62	39	23	52	40
Leaves:						
Green	69	31	18	13	73	71
Fallen	51	49	23	26	50	45
Fleshy fruits	59	41	21	20	64	69
Mushrooms	61	39	37	2	93	95
Lichens (*Alectoria sarmentosa*)						4/ 73

1/ Source: Short 1981.

2/ A is estimated true dry-matter digestibility based on cell wall content and composition.

3/ B is estimated true dry-matter digestibility measured by the nylon-bag technique.

4/ Annual mean, from Rochelle (1980) for in vitro dry-matter disappearance.

Table 4—Chemical composition of 11 winter forage species collected in January[1]

Species	Cell solubles	Cellulose	Hemi-cellulose	Lignin/cutin	Ash	Nitrogen
			Percent			
Pyrola secunda	78.3	15.1	3.0	3.0	0.6	3.14
Tiarella trifoliata	76.3	18.3	2.4	2.6	.4	2.00
Rubus pedatus	67.3	17.3	11.0	3.8	.6	1.94
Cornus canadensis	66.8	18.1	6.8	7.8	.5	1.66
Coptis aspleniifolia	61.1	25.4	8.2	4.7	.6	1.62
Rubus spectabilis	36.0	27.5	16.8	18.7	1.0	1.79
Tsuga heterophylla	54.8	24.3	5.5	14.8	.6	1.50
Vaccinium spp.	37.9	29.8	13.1	17.4	1.8	1.46
Menziesia ferruginea	38.5	25.5	15.4	19.0	1.6	1.39
Usnea spp.	84.0	2.7	11.8	1.3	.2	.56
Liverwort	49.2	20.6	23.4	3.0	3.8	1.89

1/ Calculated from data in Schoen and Wallmo (1979, p. 80).

Table 5—Plant species composition of rumen contents from 14 Sitka black-tailed deer collected during virtually snow-free conditions at sea level on Admiralty and eastern Chichagof Islands, 1981 1/

Plant species	Rumen content (oven-dry weight) January (n=4)	February (n=9)	March (n=1)	Mean (n=14)	Range
	Percent				
Forbs and ferns:					
Coptis aspleniifolia	12.9	4.8	18.6	8.1	0 -18.6
Dryopteris dilatata	0	5.4	.1	3.5	0 -37.9
Lysichiton americanum	6.0	1.7	16.2	4.0	0 -18.6
Tiarella trifoliata	.4	2.8	.4	1.9	0 -11.5
Half-shrubs:					
Cornus canadensis	37.5	35.5	16.1	34.7	13.6-54.1
Empetrum nigrum	.1	0	0	2/	0 - .3
Phyllodoce aleutica	0	0	5.5	.4	0 - 5.5
Rubus pedatus	10.4	6.0	6.0	7.3	1.1-31.9
Vaccinium vitis-idaea	.1	2/	1.6	.2	0 - 1.6
Vaccinium spp. 3/	.7	1.0	1.9	1.0	0 - 2.9
Shrubs and trees:					
Chamaecyparis nootkatensis	0	15.7	.6	10.1	0 -46.8
Ledum palustre	4.8	.9	11.3	2.8	0 -18.9
Picea sitchensis	0	2/	0	2/	0 - .1
Rubus spectabilis	7.5	0	0	2.1	0 -17.0
Tsuga heterophylla	1.0	9.8	3.5	6.8	.4 -25.8
Vaccinium spp. stems	3.2	3.1	4.6	3.2	0 - 9.9
Unidentified stems	3.8	6.8	10.6	6.2	
Lichens:					
Usnea spp.	1.4	.6	.3	.8	0 - 3.0
Other lichens	.2	3.3	.3	2.2	0 -14.1
Graminoids	2/	.1	.3	.1	0 - 1.0
Alga:					
Fucus furcatus	6.9	1.1	2.2	2.8	0 -16.8
Mosses	.1	.2	.1	.2	0 - .9
Unknown	2.9	.7	0	1.3	

1/ Source: D. E. Spalinger 1981, unpublished report on file at Forestry Sciences Laboratory, Juneau.

2/ Less than 0.05 percent.

3/ Decumbent, evergreen variety.

Accumulation of snow affects availability of forage species differentially. The lower, evergreen herb layer containing the higher quality forage is covered before the lower quality conifers and tall, deciduous shrubs (Harestad 1979). The effect of snow on forage quality is, in general, disproportionately greater than its effect on forage quantity. In winter, when the herb-layer, evergreen forages are buried, energy deficits increase greatly, despite the abundance of deciduous browse and conifers (Kucera 1976, Markgren 1971, Perzanowski 1978).

Forest Vegetation and Patterns of Habitat Use

Secondary succession.—The old-growth, commercial forest is characterized by uneven-aged stands that are more than 250 years old (Alaback 1980, Franklin and others 1981) and dominated by western hemlock and/or Sitka spruce, with an understory composed primarily of ericaceous shrubs, ferns, and forbs. Dominant trees tend to be massive, and the understory is relatively productive (≈800 kg/ha) and rich in numbers of species (Alaback 1980, 1982). The successional sequence following windthrow is difficult to characterize, because the degree and frequency of disturbance ranges from scattered trees being blown down or dying to entire stands being blown down at once (Alaback 1980, 1982). Windthrow of large trees or small groups of trees appears to be the most frequent type of disturbance in old-growth forests (Brady and Hanley 1984).

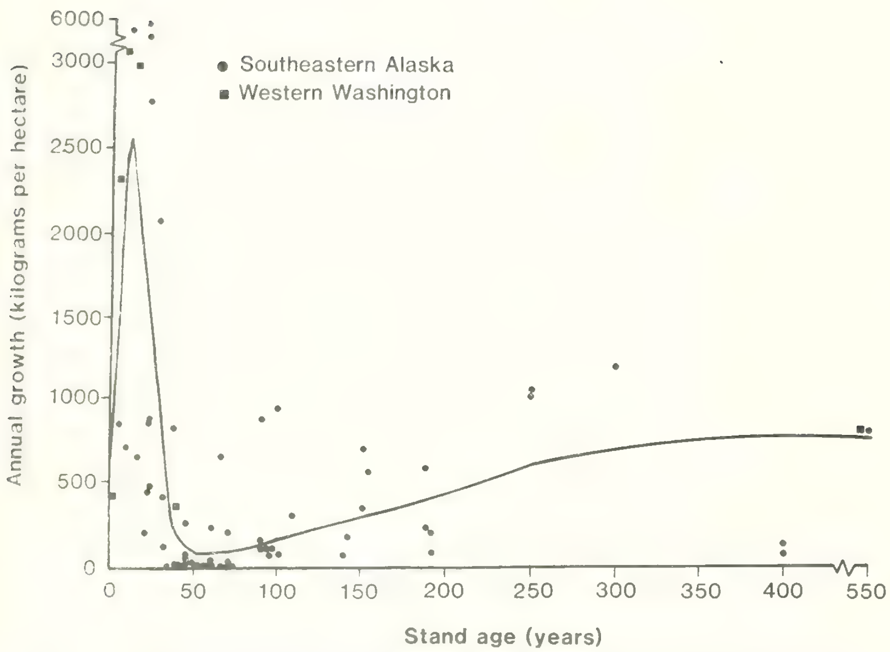

Figure 5.—Current annual growth of understory shrubs, forbs, ferns, and graminoids in relation to stand age for southeastern Alaska (Alaback 1980) and the *Abies amabilis* Zone of western Washington (Hanley 1980). Line has been fitted to means calculated at 10- to 20-year intervals.

Following clearcutting of relatively well-drained sites, shrubs dominate for the first 15 to 25 years and then young conifers take over (Alaback 1980, Harris 1974). Following closure of the canopy in young conifer stands, vascular understory species are virtually eliminated for about a century before they begin to reestablish themselves (Alaback 1982). Availability of the current annual growth of vascular understory species fluctuates greatly during this successional sequence, ranging from as high as 5 500 kilograms per hectare at about 20 years to zero at 50 years (fig. 5). This pattern is similar to that in the coastal Pacific Northwest (Hanley 1980, fig. 5), except that up to about 30 years levels of shrub biomass produced tend to be much greater in southeastern Alaska, while from 30 to 150 years levels of understory biomass and production tend to be much lower (compare Alaback 1980, Hanley 1980, Long 1976, Long and Turner 1975, Turner and Long 1975). There is also a striking lack of dominant herbs following clearcutting in southeastern Alaska. For example, the current annual growth of herbaceous vegetation in clearcuts 8 to 13 years old in the Cascade Range of western Washington was 2 100 kilograms per hectare (Hanley 1980) compared to about 400 kilograms per hectare in southeastern Alaska (Alaback 1980); respective levels of current annual growth of shrubs were 1 100 versus 2 400 kilograms per hectare.

The possibilities of modifying secondary succession in southeastern Alaska by silvicultural treatment are being investigated, but the responses of understory species are poorly understood (Kessler 1982). Also of unknown consequence is the pattern of secondary succession following logging of second-growth stands without vascular understories. Widely dispersing, adventitious species may become increasingly common in young clearcuts (Brady and Hanley 1984).

If carrying capacity for deer is directly proportional to the production of forage in a particular habitat, then carrying capacity should increase immediately following clearcutting of the old growth and decrease with canopy closure of the second growth (Brown 1961). Besides the quantity of forage produced, however, it is important to consider what forage is available, especially in winter. The frequency, depth, and duration of snowpacks are critical in the relationship between forage production and carrying capacity for deer. More snow accumulates in recent clearcuts than in forests, thereby reducing the availability of forage and increasing the energy costs of travel for deer (Fitzharris 1975; Gates 1968; Harestad 1979; Jones 1974, 1975; Schoen and Wallmo 1979; Weger 1977). Under snow conditions, the carrying capacity of old-growth forests is much greater than that of any earlier seral community (Harestad and others 1982). Arboreal lichens that are important sources of energy for deer during winter are available in significant quantities only in old-growth forests (Bunnell 1979, Bunnell and Eastman 1976, Rochelle 1980).

Wallmo and Schoen (1980), working on southern Admiralty Island and eastern Chichagof Island, examined deer use of old-growth and younger stands. Data based on fecal pellet groups revealed that during both summer and winter deer used old-growth forest more than recent clearcuts or closed-canopy second-growth forest (fig. 6). Virtually identical patterns have been observed during winter on Annette Island on the southern end of the Alexander Archipelago (Rose 1982). Farther south, on Vancouver Island, British Columbia, old-growth forest was preferred during winter (Bunnell 1979, Harestad 1979, Jones 1974 and 1975, Rochelle 1980), but recent clearcuts were used more heavily during summer (Harestad 1979). This was also true on summer range in western Washington (Hanley 1980).

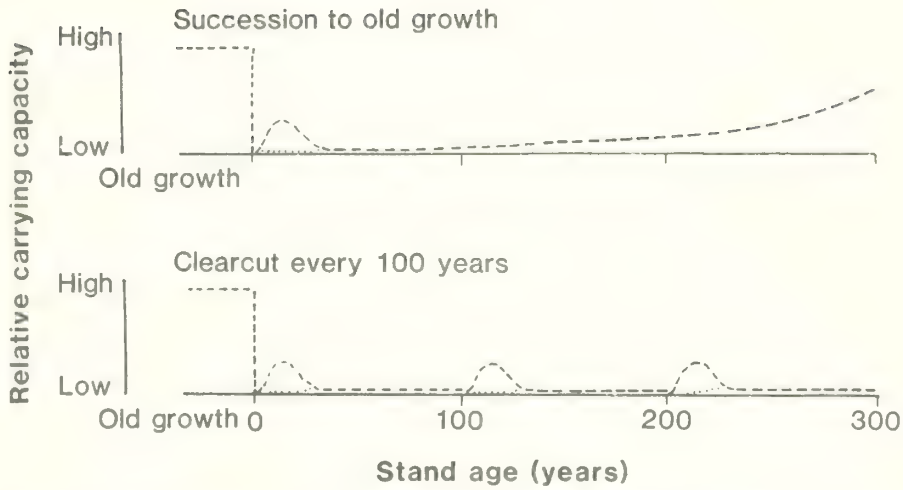

Figure 6.—Hypothesized changes in carrying capacity for deer of western hemlock-Sitka spruce forest in southeastern Alaska. In recent clearcuts, winter carrying capacity may be reduced to zero by snow (adapted from Wallmo and Schoen 1980, used with permission).

Table 6—Preliminary classification of 3 southeastern Alaska forest overstory types that comprise most of the commercial forest land[1]

Overstory type (Level IV)	Community type (Level V)
Sitka spruce--occupies wet sites, primarily alluvial flood plains	Picea sitchensis/Oplopanax horridum-Rubus spectabilis/Cornus canadensis
Sitka spruce-western hemlock--occurs on moist sites	Picea sitchensis-Tsuga heterophylla/Lysichiton americanum/Sphagnum spp. Picea sitchensis-Tsuga heterophylla/Vaccinium ovalifolium-V. alaskensis-Menziesia ferruginea Picea sitchensis-Tsuga heterophylla/Moneses uniflora-Tiarella trifoliata/Mnium spp.
Western hemlock-Sitka spruce-(western redcedar)--widespread throughout southeastern Alaska	Tsuga heterophylla-Picea sitchensis-(Thuja plicata)/Vaccinium ovalifolium-V. alaskensis/Rhytidiadelphus loreus. Tsuga heterophylla-Picea sitchensis-(Thuja plicata)/Lysichiton americanum/Sphagnum recurvum.

1/ Viereck and Dyrness, 1980.

The central assumption of all of these studies is that use of habitat is roughly proportional to habitat quality (capacity to produce and/or support deer). This assumption is well founded on theoretical grounds (Brown 1969; Doyle 1975; Fretwell 1972; Fretwell and Lucas 1970; Lack 1954; Levins 1962, 1968; Orians 1980; Templeton and Rothman 1974). On northern Vancouver Island, however, evidence is mounting that deer populations actually decline following logging (Hebert 1979) as would be predicted by models based on habitat use (Harestad 1979, Wallmo and Schoen 1980).

Variation within the forest.—Viereck and Dyrness (1980) listed 14 forest overstory types found in southeastern Alaska. Only 3 of the 14 comprise a substantial proportion of the commercial forest lands: (1) Sitka spruce, (2) Sitka spruce-western hemlock, and (3) western hemlock-Sitka spruce-(western redcedar). The latter two types intergrade almost imperceptibly with one another. Although Viereck and Dyrness tentatively subdivided these three types into six community types (table 6), much work lies ahead to identify patterns of species associations in forest understories in southeastern Alaska.

Schoen and others (1981) identified three major understory species associations within the commercial spruce-hemlock forests on eastern Chichagof and Admiralty Islands: (1) huckleberry/bunchberry dogwood-five-leaved bramble-goldthread, (2) devilsclub/skunk cabbage-violet-foamflower, and (3) single delight-conifer seedlings. When individual stands were plotted in relation to principal components, however, no distinct community types were evident, indicating that the species associations were best considered as gradients rather than community types per se.[2] The huckleberry/bunchberry dogwood-five-leaved bramble-goldthread association was most common on well-drained sites. The devilsclub/skunk cabbage-violet-foamflower association was most common on wet sites, with devilsclub dominating on shallow, rocky soils with flowing water and skunk cabbage dominating on poorly-drained, mucky soils with standing water. The single delight-conifer seedling association appeared to be related to dead and down debris where single delight and conifer seedlings became established above the underlying forest floor. This association, therefore, appeared to be independent of the other two associations. These analyses are tentative, however, and need further work.

2/ Schoen, J. W.; Kirchhoff, Matthew D.; Hanley, Thomas A. Unpublished data on file at Forestry Sciences Laboratory, P.O. Box 909, Juneau, AK 99802.

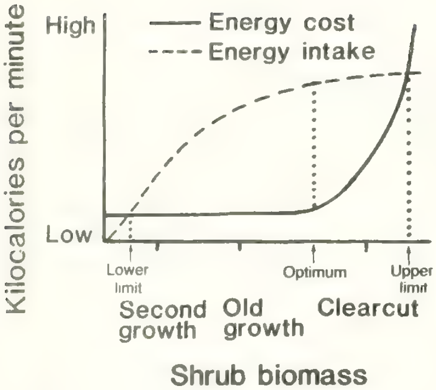

Figure 7.—A foraging benefit-cost model of habitat selection in southeastern Alaska old-growth commercial forest, recent clearcuts, and closed-canopy second-growth forest. Deer should prefer habitat where the difference between energy intake and energy cost is greatest. There is an optimal level (or range of levels) of shrub biomass as well as lower and upper limits where energy intake is not less than energy costs.

The forest overstory influences the understory through its effect on microclimate and availability of both above- and below-ground resources. Understory production tends to be negatively associated with overstory vigor and density, but the relationships between variables vary with stand structure (Alaback 1980). In Alaback's analysis of 62 stands, understory production was negatively correlated with overstory canopy coverage, foliar biomass, and stand volume in young (<90 years), even-aged, second-growth stands but was positively correlated with mean tree diameter, basal area, and stand volume in mature (>90 years), even-aged and uneven-aged, old-growth stands. The positive correlations in mature and old-growth stands were related to increased space between large trees, which was accompanied by an increase in mean tree diameter and volume as stands aged. Increased space accompanies breaking up of the canopy, as stands age beyond silvicultural maturity and understory biomass and productivity increase (Bormann and Likens 1979, Franklin and others 1981).

In southeastern Alaska forests, patterns of habitat use by deer have been studied most intensively during winter and early spring—seasons when deer depend most heavily on forests. Studies (Barrett 1979; Bloom 1978; Leopold and Barret 1972; Rose 1982; Schoen and others 1979, 1981) show that the habitats of greatest value to deer during periods of snow accumulation are old-growth, western hemlock-Sitka spruce forest of moderate to high volume (>≈20,000 board feet per acre), with an understory of huckleberry, bunchberry dogwood, and five-leaved bramble. This combination of structural and compositional characteristics apparently resulted in a high degree of snow interception and redistribution by the massive forest canopy, as well as high-quality, nutritious forage available in the understory.

During snow-free periods, however, the relative importance of habitats may shift. Herb-layer, evergreen plants (for example, bunchberry dogwood and five-leaved bramble) continue to be the forage of highest quality, but may be more available in more open-canopied, lower-volume forests (Schoen and others 1982).

Wet sites with an understory dominated by devilsclub or skunk cabbage received less use during winter than well-drained sites with understories dominated by huckleberry (Schoen and others 1981). During early spring, however, skunk cabbage is one of the first species to produce new growth above ground, and deer use it heavily (Klein 1965). Forest patches where skunk cabbage is abundant receive high use by deer during this relatively brief but important time.

Patterns of forest use by deer, therefore, shift through the winter and spring with changes in snow conditions and plant phenology. Although moderate- to high-volume, old-growth, western hemlock-Sitka spruce forests with an understory of huckleberry, bunchberry dogwood, and five-leaved bramble may be the most important kind of habitat for deer during deep snow accumulations, other kinds of forested habitat may be of greater value during snow-free periods. Variety of habitat on the winter range is important.

A benefit-cost model of habitat quality.—Why might old-growth forest be preferred to recent clearcuts that are snow-free, even during summer? This pattern of habitat use appears, superficially, to be contrary to the behavior of black-tailed deer in more southern latitudes. Wallmo and Schoen (1980) suggested that logging slash may be the primary factor that restricts deer use of recent clearcuts during snow-free periods. Another hypothesis is that deer use clearcuts less because forage quality is lower. This is based on data presented by Billings and Wheeler (1979), Van Horne (1982), and Rose (1982) that indicates nitrogen content of understory plants is greater in old-growth understory than in clearcuts. A third hypothesis is that in southeastern Alaska deciduous shrubs quickly form such dense stands that any benefits from increased forage availability in clearcuts are more than offset by increased energy costs of travel.

All three of these hypotheses could be correct and interactive, as illustrated in a simple, generalized model of habitat selection (fig. 7). As the biomass of herb- and shrub-layer vegetation increases, intake of metabolizable energy increases rapidly at first and then levels off at a saturation level. It is also assumed that energy costs of locomotion are low and relatively stable when levels of shrub biomass are low and medium but increase exponentially when levels of shrub biomass are high. Habitat quality is measured by the difference between intake and cost, with optimal habitat being the level at which intake minus cost is maximum. Costs of foraging exceed benefits when levels of biomass are either very low or very high. At the points where the two functions intersect, costs are equal to benefits.

Even-aged second-growth, uneven-aged old-growth, and recently clearcut habitats in southeastern Alaska should have low, medium, and high levels of shrub biomass as shown on the gradient in figure 7. If this is the case—as it appears to be—snow-free clearcuts in western Washington and Oregon, with lower peak levels of shrub biomass than those in southeastern Alaska, should be of greater value to deer.

Additional support of this model comes from the convex parabolic curves that Willms (1971:85-96) observed for the relationship between deer use and shrub canopy coverage on Vancouver Island. Willms noted that densities of deer pellets in clearcuts were positively correlated with low and medium levels of shrub cover but were negatively correlated with high levels of shrub cover. This relationship would be predicted from figure 7.

The benefits and costs depend on more than availability of forage and amount of shrub biomass. Forage quality is important (Moen 1973, Wallmo and others 1977), as well as relationships involving thermal energy exchange (Beall 1974, Moen 1973), amount of logging slash (Lyon 1976, Lyon and Jensen 1980), and snow depth (Drolet 1976, Gilbert and others 1970). These factors can be incorporated into the model by altering the benefit and cost curves.

Differences in forage quality affect intake. As forage quality increases, the net intake of metabolizable energy (that is, foraging efficiency) increases (fig. 8a). This results from greater nutrient value per unit of forage and a greater passage rate of ingested forage. With the latter, deer have opportunities for more bites per unit of time and/or more time for selecting bites (Hanley 1982b). As forage quality increases, the difference between energy intake and energy cost increases. The reverse is true where forage quality decreases.

Difference in the thermal environment may also affect foraging costs. As thermal energy losses from deer increase, the energy expended by deer to maintain homeothermy increases (fig. 8b). Costs of thermal energy exchange are in addition to foraging costs (Moen 1973) and raise or lower the cost curve with little or no effect on its shape. As thermal energy costs increase, the difference between energy intake and energy cost decreases.

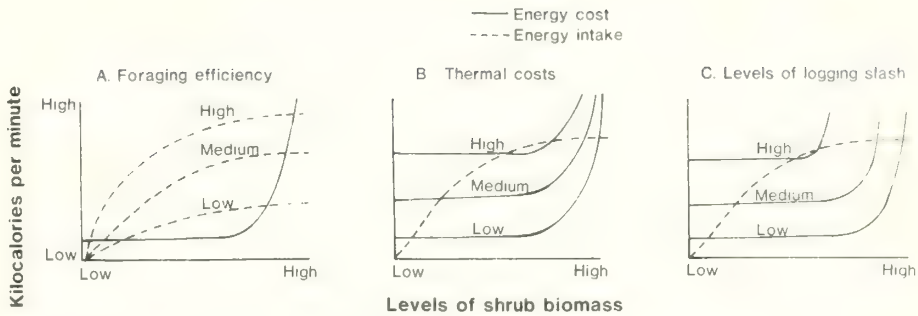

Figure 8.—Factors that interact to affect the benefit-cost relationships for deer.

Depth and amount of logging slash also affect foraging costs. If the effects of logging slash and shrub biomass are interactive (that is, each exaggerates the effect of the other), the result is raising the cost curve and sharpening its inflection with increases in logging slash (fig. 8c). As the amount of logging slash increases, the difference between energy intake and cost decreases. While changes in forage quality, thermal environment, or amount of logging slash affect the range of habitats that are suitable for deer, only changes that interact with shrub biomass (in this case, logging slash) affect the level of shrub biomass considered to be optimal.

The effects of snow are more complicated. As snow depth increases, forage availability and quality decrease and foraging costs increase. In general, energy requirements increase exponentially with snow depth, while food availability decreases (fig. 9). If the snow is capable of supporting a deer's weight, then it effectively reduces the level of shrub biomass available and the amount of slash. Snow reduces forage quality by burying the herb-layer plants but may or may not add to the energy costs of travel, depending on the depth to which the deer sinks. The overall effect of snow is to restrict the range of suitable habitats and to lower the quality of all habitats.

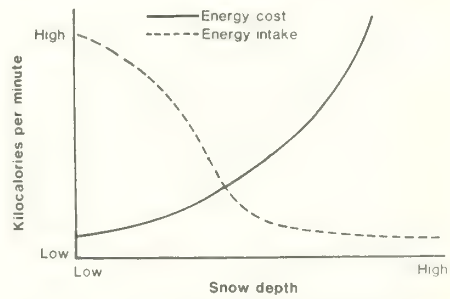

Figure 9.—A benefit-cost model illustrating the effect of snow depth on the energy intake of deer and energy costs of foraging (adapted from Harestad and others 1982, used with permission).

The problem faced by the deer is choosing the habitat patch and diet where the foraging benefit is greatest. Choice of habitat determines foraging costs; the amount of forage available and choice of diet determine energy intake.

Home Range

To a large extent, the movements of an individual deer are confined to a limited area known as home range. Deer, especially females, appear to learn their home ranges from association with their mothers during their first year or two (Dasmann and Taber 1956, Nelson and Mech 1981). Fidelity to their traditional home ranges can be so great that deer will starve to death rather than travel a few kilometers to abundant forage (Dasmann and Taber 1956). The summer home ranges of migratory deer are usually larger than their winter home ranges, and bucks tend to have larger home ranges than does. Bucks are also more mobile and more likely to establish new home ranges than does (Dasmann and Taber 1956, Miller 1970, Nelson and Mech 1981, Robinette 1966). Home range determines what habitats are available to individuals, and, to a large degree, tradition determines the distribution of deer over the landscape (Nelson 1979). Since quality of habitat is not uniform, some deer fare better than others (Taber and Dasmann 1957).

Home ranges of deer in southeastern Alaska (Schoen and others 1981) are comparable in size to those reported for Columbian black-tailed deer in the Pacific Northwest (Hanley 1980, Harestad 1979, Miller 1970). Variation between individual deer probably reflects differences in early experience as well as the habitat composition of their home ranges (Schoen and others 1981). About two thirds (11 of 17) of the Sitka black-tailed deer captured on winter range and monitored the year around by telemetry by Schoen and others (1982) made distinct migrations between winter and summer ranges; the other six were year-round residents of their winter ranges. All 13 deer for which 2 or more years of data were available utilized similar summer and winter home ranges between years, suggesting strong fidelity to home ranges (Schoen and others 1982). "Migratory" deer generally summer at relatively high elevations, while "resident" deer remain in low-elevation habitats the year around. This phenomenon is common with Columbian black-tailed deer in the coastal Pacific Northwest as well (Harestad 1979, Taber and Hanley 1979).

Seasonal movements.—In early spring, most deer in southeastern Alaska are still on winter range, which is usually below 300 m (Klein 1965, Schoen and others 1981). Upper elevations vary from 100 m during years of heavy snow accumulation and/or on northerly exposures, to 600 m during light snow and/or on southerly exposures. As the snowline recedes, deer move up and make greater use of areas with new, green vegetation. By late spring, high quality forage is abundant, and migratory deer move near their summer ranges. Spring home ranges of 13 telemetered deer reported by Schoen and others (1981) ranged from 30 to 12 369 ha and averaged 1 521 ha. Distances (straight-line) between summer and winter ranges for telemetered migratory deer have been observed between 1.6 and 72.5 km (Schoen and others 1981). Most deer probably move less than 10 km between winter and summer home ranges. In general, spring is a transition period between summer and winter ranges for migratory deer. For resident deer, some of which spend the whole year—and perhaps their entire lives—within 200 ha, only localized shifts occur. Parturition occurs in late May and early June, usually in lower elevation habitat.

During summer, migratory deer on the mainland and larger islands have access to abundant, high quality forage in alpine and subalpine habitats (Klein 1965) and prefer these habitats (Schoen and others 1981). The summer home ranges of the 13 telemetered deer reported by Schoen and others (1981) ranged from 40 to 563 ha, and averaged 233 ha. They were distributed from sea level (resident deer) to above 1 000 m (migratory deer).

The fall home ranges of 12 telemetered deer reported by Schoen and others (1981) averaged 505 ha and ranged from 64 to 1 307 ha. Migratory deer continue to utilize alpine and subalpine habitats through early fall. After the first heavy frosts, when much of the herbaceous forage is killed, deer move down to the upper forest. They may remain at higher elevations throughout fall unless snow begins to accumulate. Some deer move up and down with the changing snowline (Schoen and others 1979, 1981). Some move to lower elevations following the first snow and stay there; others remain in areas where snow accumulations exceed 30 cm. During the rut from late October to early December, migratory and resident deer probably are not segregated.

Winter through early spring is the period of greatest year-to-year variation in deer distribution. It also is the period when forage is most limited and the time of highest mortality. Winter home ranges of 15 of the telemetered deer reported by Schoen and others (1981) ranged from 42 to 302 ha and averaged 122 ha. In some years, elevations below 300 m are nearly free of snow throughout the winter. In other years, snow may accumulate below 150 m for 4 to 5 months, with extensive snow at sea level. Early winter snow seldom remains long at lower elevations because of the strong maritime influence. As rain melts the snow, many migratory deer that moved to lower elevations after the first snow move, again, into the higher forest, often as high as 600 m or higher (Schoen and others 1981, 1982). Throughout the winter resident deer also move up and down within their home ranges depending on changing snow levels. It appears that many deer winter as high as snow conditions allow (Barrett 1979, Merriam 1968, Olson 1952, Schoen and others 1981). The mean elevation for 12 telemetered deer during two mild-to-average winters on Admiralty Island was 111 m, with individual variation from 30 to 237 m (Schoen and others 1981). Individual animals varied greatly in mean distance from the beach. When snow is deep at sea level, the beach and beach-fringe forest become the last refuge for many deer. In less severe conditions, the best winter habitat may be many kilometers from the beach.

Influence of Deer on Vegetation

Deer affect vegetation through selective consumption of plants and plant parts, and by trampling. As a result, palatable woody stems and succulent forbs with growing tissue located above ground tend to decrease, while graminoids and forbs with growing tissue at or below the ground surface may increase (Hanley and Taber 1980). If deer are abundant, they may create an open-appearing landscape (Hanley and Taber 1980).

Management Implications

Deer severely altered the vegetation on Coronation Island in southeastern Alaska (Klein 1965). Deer use resulted in "hedged" forms of ovalleaf huckleberry, red huckleberry, red elderberry, and even western hemlock and Sitka spruce. Klein believed that excessive use by deer had eliminated important winter and summer forage species on the island. Similarly, high populations of introduced Sitka black-tailed deer on the Queen Charlotte Islands in British Columbia, have affected the vegetation so heavily that foresters are concerned about future regeneration of western redcedar, Alaska yellow cedar, western hemlock, and even Sitka spruce.[3] Damage to young Douglas-fir has been a problem for foresters in the Pacific Northwest for many years (Cowan 1945, Crouch 1981). Moderate levels of browsing, however, may reduce competition by shrubs and benefit young conifers (Crouch 1974, Hanley and Taber 1980).

As sources of high quality forage decrease, deer consume lower quality forage, resulting in decreased quality of diet (Carpenter and others 1979, Klein 1965, Taber and Dasmann 1957). The effects of decreased diet quality on Sitka black-tailed deer were demonstrated in Klein's (1962, 1964, 1965) comparisons of deer populations and their habitat on Woronkofski and Coronation Islands in southeastern Alaska. For a variety of reasons, including mild winter weather and the absence of wolves on Coronation Island, deer populations there were believed to exceed the normal carrying capacity of their habitat, with a resulting decrease in high quality forage. Deer on Woronkofski Island, in contrast, had access to a greater proportion of alpine and subalpine habitat in summer, but were subject to more severe winter weather and wolf predation. They exceeded the carrying capacity of their habitat much less often than the deer on Coronation Island. Deer on Coronation Island had lower body weights and growth rates, a lower ratio of fawns to adult females, an older average age, a less even sex ratio, and higher natural mortality in young animals than deer on Woronkofski Island. These attributes are characteristic of lower quality diet.

[3] Pojar, Jim; Lewis, Terence; Roemer, H.; Wilford, D. J. Relationships between introduced black-tailed deer and the plant life of the Queen Charlotte Islands. British Columbia: B. C. Ministry of Forests. Unpublished report on file at Research Branch, B. C. Ministry of Forests, Smithers, B.C., Canada. VOJ 2NO. 1980. 63 p.

The habitat relationships of Sitka black-tailed deer provide only a general perspective for evaluating local conditions and circumstances and for developing management prescriptions. Specific situations in each area must be considered. In southeastern Alaska the variation in natural vegetation and climate are particularly important. The amount and quality of vegetation varies within both old-growth and second-growth forests. Climate varies both spatially and temporally. Snow influences forage availability and is critically important in managing habitat for both deer and timber. The frequency, depth, and persistence of snow varies greatly throughout the range of Sitka black-tailed deer and often over very short distances. Topography and prevailing climate are major factors which must be considered in developing local management prescriptions.

Wolf predation can be a significant factor in controlling deer populations in southeastern Alaska (Klein 1981). Although little is known about deer-wolf relationships in this region, where wolves are present, deer populations probably are slow to recover from die-offs during the occasional severe winters. Theoretically, if the fecundity of a deer population declines below a threshold level, a rapid decline in deer density is likely to result, with predation as the proximate cause (Van Ballenberghe and Hanley 1984). Management practices that lower the carrying capacity of the habitat can initiate population declines. Management to maintain habitat and prevent declines in deer populations seems more logical than trying to reverse deer declines by controlling wolves (Van Ballenberghe and Hanley **1984).**

Although management prescriptions must be based on local circumstances, general principles could be applied universally. Understanding the functional relationships between deer and their habitat will help. Physiological requirements of deer under various environmental conditions can help define required and optimal habitats. Optimum habitat, however, cannot be defined in terms of specific structural or compositional features throughout the range of Sitka black-tailed deer. Optimal elevation, stand volume, or understory species composition, for example, vary with other environmental circumstances and are not fixed. Beyond understanding the functional relationships, the following guidelines may help focus attention on specific features of habitat.

Critical Winter Range

The concept of "critical winter range" means habitat that is of great importance for deer survival and is in relatively short supply during severe winter weather (in southeastern Alaska, periods of deep snow accumulation). Critical winter range is the optimal habitat during climatic conditions that are most responsible for winter mortality of deer. It is not optimal habitat under all winter conditions and, alone, it may not even be adequate to support deer throughout an entire winter. Other habitats are important for relieving browsing pressure on critical winter range during periods when snow is not deep.

From a deer perspective, there probably are three thresholds of snow depth. The first is the depth at which evergreen forbs and herb-layer shrubs become buried—approximately 10 cm. The second is when deer sink in the snow beyond front knee height (approximately 25 to 30 cm) and energy costs for locomotion increase greatly[4] (fig. 2). The third threshold is the point at which tall shrubs become buried. When snow is beyond that depth, deer diet consists almost entirely of low quality conifer foliage, and the energy costs for locomotion are extremely high. Crusting of the snowpack reduces sinking depth greatly, but forage remains buried. For management purposes, therefore, snow deeper than 25 to 30 cm probably should be considered "deep snow."

[4] Parker, K. L. and Robbins, C. T. (Dept. Zoology, Wash. State Univ.) Personal communication on file at Forestry Sciences Laboratory, P.O. Box 909, Juneau, AK 99802.

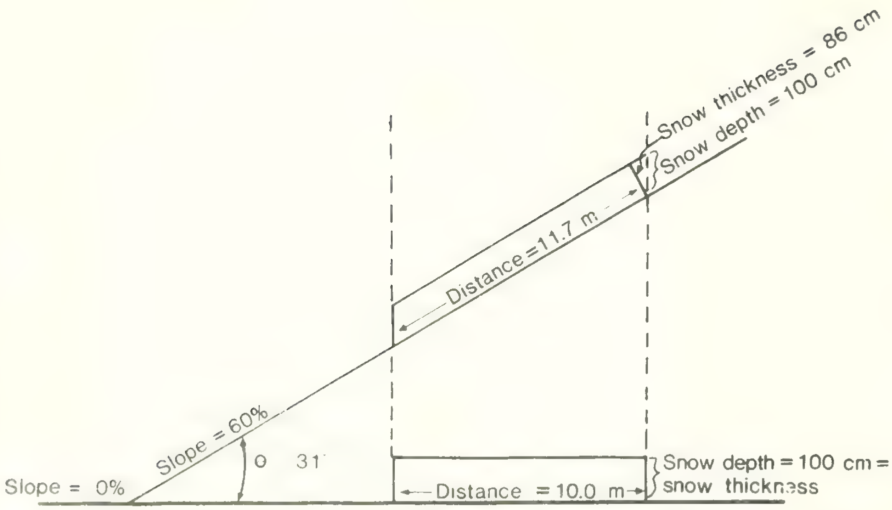

Figure 10.—Snow thickness is less on steep slopes than on moderate slopes or level areas because snow is spread over more ground surface. A slope of 60 percent (31°) has a ground surface area 1.17 times that of a level area; hence, snow thickness is 86 percent that of the level area. Snow depth, however, is the same as on the level area.

Habitat features most useful in identifying critical winter range are climate, topography, and vegetation. Prevailing winter climate varies from frequent, heavy snowfall in the northeastern part of the Alexander Archipelago to relative absence of snow in the lower elevations of the Queen Charlotte Islands. The elevation of critical winter range may vary substantially. Beach-fringe forest is the last refuge under severe conditions, but better habitat away from the beach or higher in elevation should not be discounted as critical winter range simply because of its location.

The degree of slope influences snow depth by its effect on the ratio of surface area to horizontal area. Assuming that snow generally falls vertically, increasing slope steepness distributes a given amount of snow over an increasingly large area, resulting in more snow being exposed to air and radiant energy (fig. 10). Other conditions being equal, the rate of snow ablation (melting and vaporization) will be proportional to surface area, and snow accumulation will be negatively related to slope angle. Of course, slope aspect, shading, and other factors (wind speed, temperature, and vapor pressure deficit) are also important.

Southerly aspects are exposed to much more potential solar radiation than northerly aspects, and radiation increases with steepness of slope on southerly aspects and decreases on northerly aspects (fig. 11). Snow ablation varies accordingly. Steep southerly slopes are probably usable longer in fall, winter, and spring than shallow southerly slopes or any northerly slopes. Considering the low sun angle at northerly latitudes during winter and the steep topography of southeastern Alaska, shading of the slope by adjacent mountains may be another factor to consider (fig. 12). Unshaded, south-facing beaches and slopes may provide more suitable habitat than shaded ones.

Two features of forest vegetation that are of greatest importance for critical winter range are: (1) a productive understory of high-quality forage, and (2) an overstory that intercepts and/or redistributes sufficient snow for understory forage to remain available to deer. On eastern Chichagof and Admiralty Islands, these conditons apparently are met most satisfactorily by low- to mid-elevation (< 300 m), old-growth, hemlock-spruce stands of moderate to high volume (30,000 to 50,000 board feet per acre), with a canopy cover of 60 to 80 percent and an understory dominated by huckleberry, bunchberry dogwood, and five-leaved bramble (Schoen and others 1981, 1982). Even at moderate snow depths (10 to 25 cm), these stands seem to provide bare spots of ground immediately beneath large trees where the highly nutritious evergreen forbs and herb-layer shrubs remain available to deer. At greater snow depths (> 30 cm), the availability of huckleberry apparently is most important. Lichen litterfall also may contribute greatly to the quality of critical winter range (Rochelle 1980).

Habitat Protection

Variety of habitat on winter range is important for deer. Open-canopied stands with abundant understory probably are most valuable during snow-free periods. Partially closed stands are more valuable during periods of snow accumulation. Much of the forest land in southeastern Alaska is of low timber volume and/or on steep slopes and currently is classified noncommercial forest. This land could provide suitable habitat during snow-free periods in perpetuity. The moderate- to high-volume, old-growth, commercial forest is a smaller part of the total area and is the major area of concern in managing for both timber and deer habitat. In areas that have winters of frequent, high snowfall and have relatively limited critical winter range for deer, the amount of old-growth, critical winter range is likely to directly determine the carrying capacity for deer.

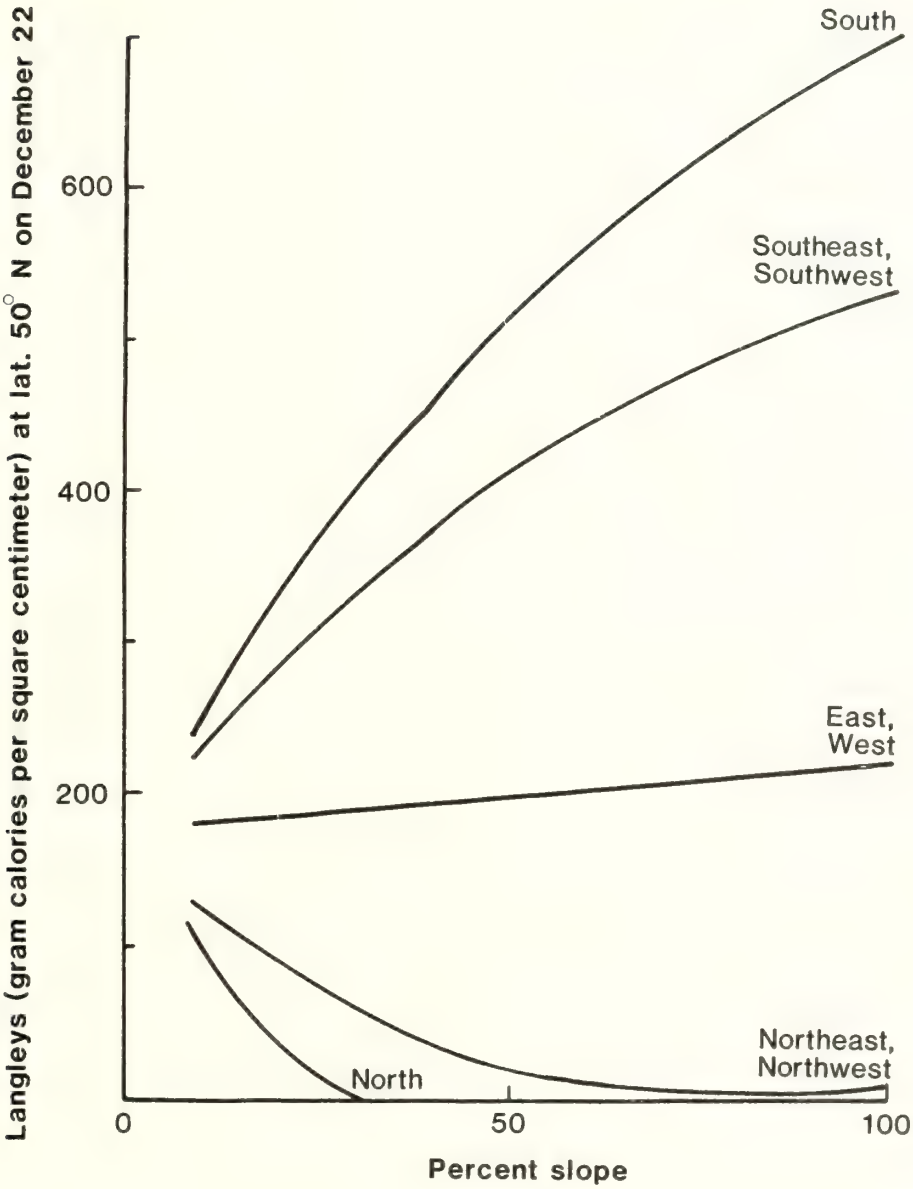

Figure 11.—Effect of slope and a
potential solar irradiation.

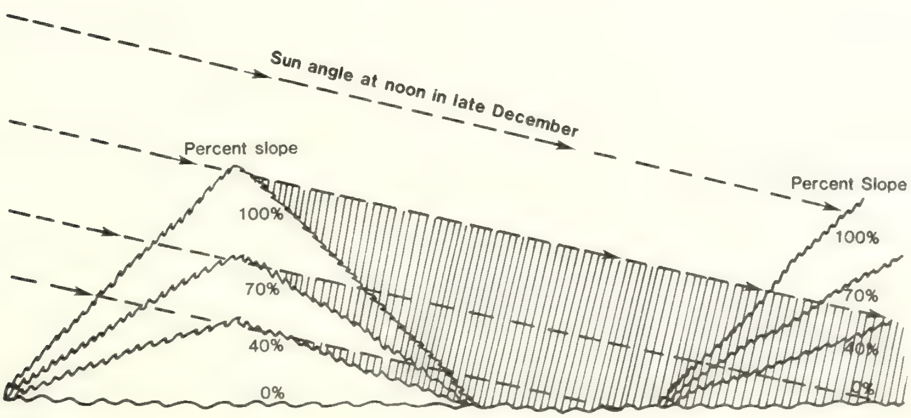

Figure 12.—Effect of slope, aspect, a
shading on solar irradiation of forest
Logging is normally restricted to slop
percent or less.

Retaining scattered blocks of old-growth forest within young, second-growth forest creates two potential problems. First, scattered patches of critical winter range potentially serve to concentrate deer, with resulting overuse of forage and decreased carrying capacity. Second, windthrow is common along the edges of clearcuts and may decrease the area of protected deer habitat. Both problems could be minimized by retaining patches of critical winter range that occur naturally within blocks of low-volume, noncommercial, or inoperable forest. Such protection would provide a variety of winter habitat within the home range of many deer and natural, wind-firm boundaries of high-volume areas. Deer with home ranges outside protected critical winter range would not know of its existence, thus minimizing problems of concentrated use.

Beach-fringe forest, the last refuge for deer moving downslope during periods of deep snow accumulation, is very important habitat that needs protection because it provides temporary but critical refuge. It cannot, however, sustain large numbers of deer for prolonged periods.

The importance of retaining areas of old-growth forest varies with the habitat composition of each management unit and the desired population levels of deer. Other factors are important also. Where the prevailing climate is mild and deep snow accumulations are rare and short in duration, a mosaic of young clearcuts within even-aged second growth probably can provide suitable winter range, as in coastal Oregon and Washington. This strategy might be appropriate management for the Queen Charlotte Islands, for example. There are no wolves on the Queen Charlottes, and deer populations would be expected to increase rapidly after an occasional, severe-winter die-off. Where wolves are present, however, the potential for recovery could be different and the long-term effects of occasional severe winters magnified.

Habitat Enhancement

Three silvicultural approaches can potentially improve deer habitat: (1) increasing forage quality, (2) increasing forage abundance and availability, and (3) improving accessibility. For recent clearcuts, the first and third are the most important; for closed-canopy, second-growth forest all three are important, but especially the first two.

Cleaning up logging slash and enforcing standards for timber utilization can reduce slash and improve deer accessibility in recent clearcuts that are free of snow. Broadcast burning in recent clearcuts also reduces slash and, sometimes, shrub biomass. Burning probably affects species composition, reducing shrubs and favoring herbs, a change that can affect quality and/or availability of deer forage. Losses of nitrogen through volatilization and leaching, however, may be an important negative consequence. Burning temporarily sets back conifer regeneration and prolongs the useful life of clearcuts for deer in snow-free seasons or areas. Precommercial thinning also may prolong the usefulness of recent clearcuts for deer if high levels of shrub biomass and/or slash do not decrease accessibility.

Precommercial and commercial thinning might improve deer habitat if they maintain and increase understory productivity and forage quality and intercept and redistribute snowfall so understory forage remains available. In either precommercial or commercial thinning, slash must be disposed of in ways that do not impede deer access.

The size and distribution of clearcuts in space and time are also important. Optimal sizes and placement are related to sizes of deer home ranges (Taber and Hanley 1979). The strong fidelity of deer to home ranges means they are unaware of habitat conditions outside their home range. Many small, scattered, irregularly-shaped clearcuts, therefore, are preferable to fewer, large, block-shaped clearcuts. Small clearcuts would result in a high ratio of forest edge to clearcut area, however, which could be a problem in areas prone to windthrow. The value of forest edge per se for deer is not well understood (Hanley 1983) and may be of no value in southeastern Alaska (Kirchhoff and others 1983).

It is important to spread the cutting over the entire elevational gradient. Clearcutting that begins at the lower elevations and moves upward results in a seral-stage gradient that is superimposed directly on the elevational gradient and severely limits deer options for finding quality habitat during winter.

Research Needs

Forest and wildlife managers need a means of quantitatively evaluating habitat quality for deer. Relationships among forest understory, overstory, and site need to be understood to predict understory species composition and productivity. Similarly, the chemical composition and nutritional value of forages need to be determined. Relationships among forest overstory, snow interception, and the availability of understory are very important. The metabolic requirements of deer and their relation to diet selection and habitat selection also are major factors. The theoretical framework for integrating these relationships into a quantitative model has been outlined in the preceding review and elsewhere[5] (Harestad and others 1982). A model based on functional relationships and driven by local climate and site factors would provide an objective means of evaluating habitat quality throughout the range of Sitka black-tailed deer.

In the short term, however,the most glaring lack of information concerns the size and productivity of deer populations. Although habitat preferences of deer have been demonstrated, population dynamics have not been studied. There are no data concerning the effects of logging on population sizes, densities, or other demographic parameters of Sitka black-tailed deer. A major reason for the lack of such information is that in habitats of dense forest, steep topography, and highly variable winter climate, it is extremely difficult to census deer populations. Nevertheless, adequate technology is a necessity for monitoring changes in deer populations and for testing the predictions of theory.

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[5] Hanley, Thomas A. Unpublished problem analysis on file at Forestry Sciences Laboratory, P.O. Box 909, Juneau, AK 99802. 1981. 89 p.

As logging of old-growth forest continues, an increasing proportion of deer habitat, especially winter range, will consist of even-aged, second-growth forests. Unmanaged, these stands provide very poor deer habitat. Research is needed on silvicultural prescriptions to improve the habitat quality of second-growth stands. Techniques for applying the prescriptions and their effects also need to be evaluated.

Current research is focusing on these needs, specifically: (1) overstory-understory relationships within old-growth and second-growth forests; (2) overstory-snow relationships; (3) forage availability and nutritional quality; (4) diet composition and quality and energy intake; (5) energy expenditure; and (6) habitat selection. Research into population dynamics and monitoring techniques is also needed.

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Metric-English Equivalents

1 meter (m) = 39.4 inches
1 centimeter (cm) = 0.39 inch
1 kilometer (km) = 0.53 mile
1 hectare (ha) = 2.47 acres
1 gram (g) = 0.035 ounce
1 kilogram (kg) = 2.20 pounds
1 kilocalorie (kcal) = 4 186 joules = 3.97 Btu
Celsius (C) = 5/9 (Fahrenheit – 32)

Scientific Names of Animal and Plant Species

Common name	Scientific name
Animals:	
Mule deer and black-tailed deer	*Odocoileus hemionus*
Sitka black-tailed deer	*Odocoileus hemionus sitkensis*
Columbian black-tailed deer	*Odocoileus hemionus columbianus*
Gray wolf	*Canis lupus*
Plants:	
Alaska yellow cedar	*Chamaecyparis nootkatensis* (D. Don) Spach
Alectoria	*Alectoria* spp.
Beard lichen	*Usnea* spp.
Bunchberry dogwood	*Cornus canadensis* L.
Devilsclub	*Oplopanax horridum* (Sm.) Miq.
Douglas-fir	*Pseudotsuga menziesii* (Mirb.) Franco
Fireweed	*Epilobium angustifolium*
Five-leaved bramble	*Rubus pedatus* Sm.
Foamflower	*Tiarella trifoliata*
Goldthread	*Coptis aspleniifolia*
Huckleberry	*Vaccinium* spp.
Ovalleaf huckleberry	*Vaccinium ovalifolium* Sm.
Pyrola	*Pyrola secunda*
Red huckleberry	*Vaccinium parvifolium* Sm.
Single delight	*Monesis uniflora*
Sitka spruce	*Picea sitchensis* (Bong.) Carr.
Skunk cabbage	*Lysichiton americanum*
Violet	*Viola* spp.
Western hemlock	*Tsuga heterophylla* (Raf.) Sarg.
Western redcedar	*Thuja plicata* Donn

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Old-growth, western hemlock-Sitka spruce forest in southeastern Alaska is an important element of the habitat of Sitka black-tailed deer. The conversion of uneven-aged, old-growth forests to even-aged, second-growth forests has generated concern about the future carrying capacity of the habitat for deer, especially where snow accumulation is common on winter ranges. Even-aged, second-growth forests produce very little forage for black-tailed deer. Young (<20 years), open stands produce greater amounts of forage than do old-growth stands. Snow accumulates to greater depths in openings than in forest, however, and forage becomes unavailable to deer as it is buried in snow. Habitat quality for Sitka black-tailed deer must be viewed as an energy benefit-cost relation. Energy intake decreases and energy expenditure increases as snow depth increases. Habitats differ in their canopy characteristics and in the amount and kind of forage they produce. The relative qualities of habitats shift with changing snow conditions. An understanding of these dynamic relationships between deer and their habitat is essential for developing management objectives for deer habitat. The current theory is largely qualitative and lacks the ability to yield unambiguous, quantitative predictions. Research is needed to quantify the key relationships between forest canopy and understory production and snow interception, and between the metabolic requirements of deer and the nutritional quality of available forage.

Keywords: Wildlife habitat management, wildlife habitat, timber management, habitat selection, deer (black-tailed), Alaska (southeast).

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